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Alternative Landfill Cover Demonstration, FY2000 Annual Data Report

Stephen F. Dwyer, Bruce Reavis, and Gretchen Newman

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ABSTRACT

A large-scale field demonstration comparing final landfill cover designs was constructed and is currently being monitored at Sandia National Laboratories in Albuquerque, New Mexico. Two conventional cover designs (a RCRA Subtitle 'D' Soil Cover and a RCRA Subtitle 'C' Compacted Clay Cover) were constructed side-by-side with four alternative landfill test covers designed for dry environments. The demonstration is intended to evaluate the different cover designs based on their respective water balance performance, ease and reliability of construction, and cost. This paper presents a general overview of the data collected to date from the ongoing demonstration. Study conclusions are not presented in the report because data is still being collected and trends are still developing. The flux rates measured from May 1997 through June 2000 are as follows:

[1] Principal Investigator
[2] Distinguished Technologist
[3] Senior Hydrologist

Year	Flux rates (mm/year)					
	Subtitle D	GCL	Subtitle C	Capillary Barrier	Anisotropic Barrier	ET
1997 (May 1 - Dec 31)	10.62	1.51	0.12	1.62	0.15	0.22
1998	4.96	0.38	0.30	0.82	0.14	0.44
1999	3.12	4.31	0.04	0.85	0.28	0.01
2000 (Jan 1 - Jun 25)	0.00	0.00	0.00	0.00	0.00	0.00
Average	4.82	1.81	0.13	0.87	0.16	0.19

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BACKGROUND

The US Department of Energy (DOE) is in the midst of a major clean-up effort of their facilities that is expected to cost billions of dollars. These cost estimates however are based on cleanup technologies currently used by DOE. Research has shown that many of these technologies have proven to be inadequate (Mulder and Haven 1995). Consequently, work has begun on the development and improvement of current environmental restoration and management technologies. One particular area under study is landfill cover performance. As part of their ongoing environmental restoration activities, the DOE has many radioactive, hazardous, mixed waste, and sanitary landfills to be closed in the near future (Hakonson., 1994). These sites, as well as mine and mill tailings piles and surface impoundments, all require either remediation to a 'clean site' status or capping with an engineered cover upon closure. Additionally, engineered covers are being considered as an interim measure to be placed on contaminated sites until they can be remediated.

The Alternative Landfill Cover Demonstration (ALCD) is a large-scale field test at Sandia National Laboratories located on Kirtland Air Force Base in Albuquerque, New Mexico (Figure 1). The project's intent is to compare and document the performance of alternative landfill cover technologies of various costs and complexities for interim stabilization and/or final closure of landfills in arid and semi-arid environments. The test covers are constructed side-by-side for comparison based on their performance, cost, and ease of construction. The ALCD is not intended to showcase any one particular cover system. The focus of this project is to provide the necessary tools; i.e., cost, construction and performance data, to the public and regulatory agencies so that design engineers can have less expensive, regulatory acceptable alternatives to the conventional cover designs.

INTRODUCTION

The ALCD landfill covers were divided into two separate bid packages known as Phase I and Phase II. The Phase I covers, constructed in the summer of 1995, include a prescriptive RCRA Subtitle 'D' Soil Cover, a prescriptive RCRA Subtitle 'C' Compacted Clay Cover, and the first of four alternative covers - a Geosynthetic Clay Liner (GCL) Cover. The RCRA Soil and Compacted Clay Covers were constructed to serve as baselines for comparison against the alternative cover designs. The Phase II covers, built in the summer of 1996, include the Capillary Barrier, Anisotropic Barrier, and Evapotranspiration (ET) Cover. Each phase of construction was competitively bid with the low bidder receiving a firm fixed price contract.

Figure 1. Aerial View of Alternative Landfill Cover Demonstration

The test covers are each 13 m wide by 100 m long. The 100 m dimension was chosen because it is representative of many hazardous and mixed waste landfills found throughout the DOE complex (approximately 2 acres in surface area). All covers were constructed with a 5% slope in all layers. The slope lengths are 50 m each (100 m length crowned at the middle with half of the length, 50 m, sloping to the east and the other 50 m sloping toward the west). The western slope component of the covers are monitored under ambient conditions (passive monitoring). A sprinkler system was installed in each of the eastern slope components to facilitate stress testing (active monitoring) of the covers (Figure 2).

Continuous water balance and meteorological data is being obtained at the project site. Data obtained to date is presented in the results section of this paper. These data will be actively collected for a minimum five-year post construction period. In addition, periodic measurements of vegetation cover, biomass, leaf area index, and species composition are being collected from each landfill cover (Wolters et al. 2000).

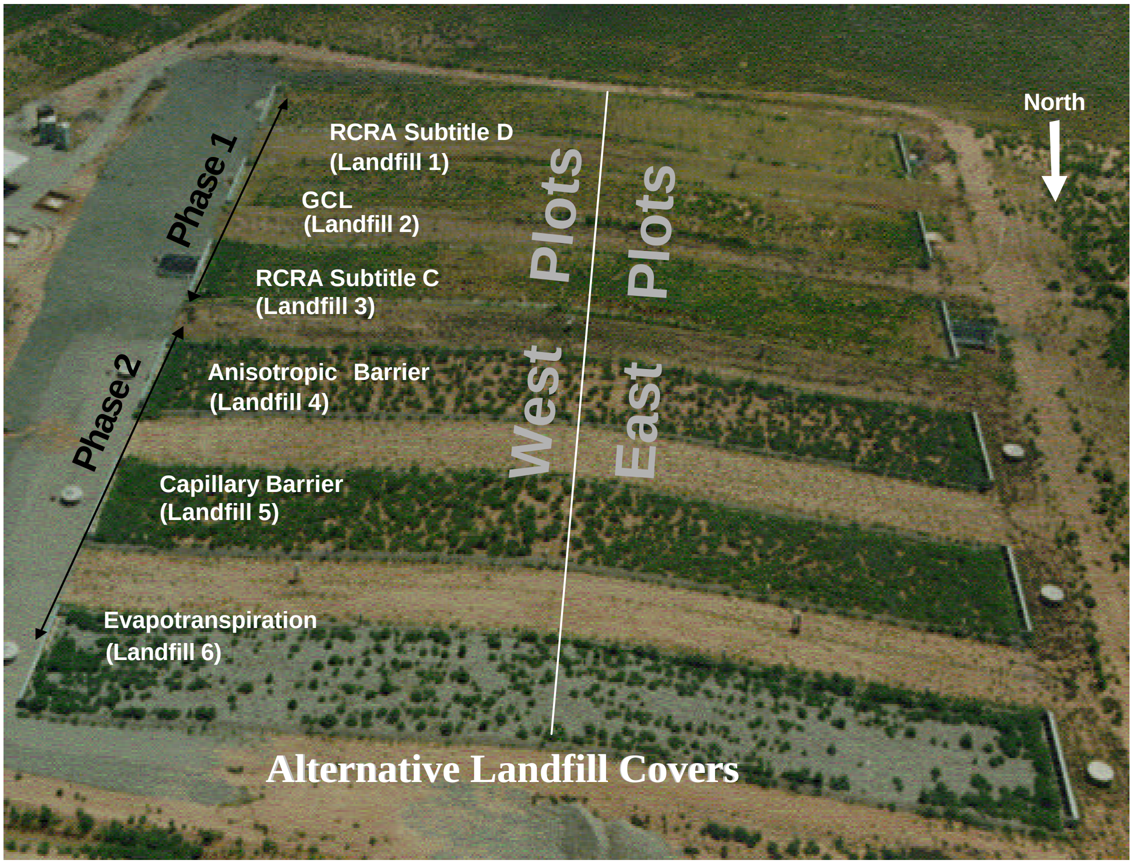

Figure 2. Test Cover Layout

The project test covers are described below.

<u>Baseline Test Covers</u>

Baseline Test Cover 1 (Landfill 1) is a basic Soil Cover installed to meet minimum requirements for RCRA Subtitle 'D' governed landfills per 40CFR258. These requirements apply to municipal solid waste landfills (MSWL) to be closed using engineered covers and are designed with intent to meet the following performance objectives:

1. cover permeability less than or equal to the permeability of the bottom liner/subsoil or no greater than 10^{-5} cm/sec;
2. minimize infiltration using no less than 45 cm of soil; and
3. minimize erosion using no less than 15 cm of topsoil for plant growth.

The installed test cover is 60 cm thick (Figure 3). It is constructed of two principal layers. The top vegetation layer is 15 cm of loosely laid topsoil. The bottom layer is a 45 cm thick compacted soil barrier layer.

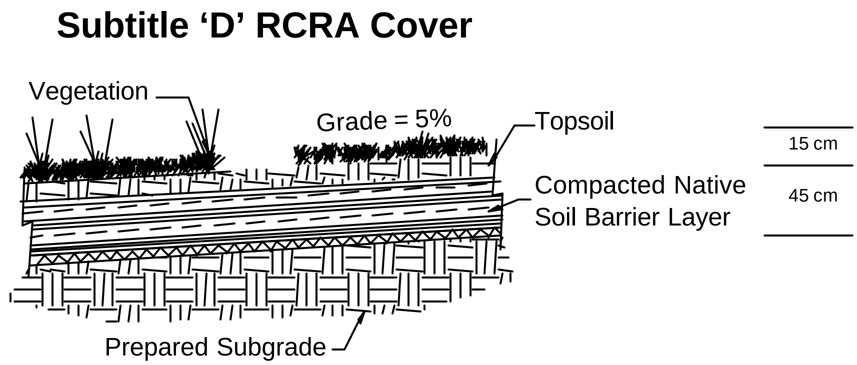

Figure 3. Profile of Baseline Test Cover 1 (Soil Cover)

Baseline Test Cover 2 (Landfill 3) is a Compacted Clay Cover designed and constructed in accordance with minimum regulatory requirements for closure of hazardous and mixed waste landfills found in 40 CFR Parts 264 and 265. These regulations are somewhat vague. They are not as specific about the details of a cover profile as those for 40CFR258. To overcome this vagueness, the EPA recommended a cover profile for the RCRA Subtitle 'C' final cover design profile (EPA 1991) described below from bottom to top:

1. A composite barrier layer consisting of a minimum 60-cm thick layer of compacted natural or amended soil with a maximum saturated hydraulic conductivity of 1 x 10^{-7} cm/sec in intimate contact with a minimum 40-mil geomembrane overlying this soil layer;
2. A drainage layer consisting of a minimum 30-cm thick sand layer having a minimum saturated hydraulic conductivity of 1 x 10^{-2} cm/sec, or a layer of geosynthetic material having the same characteristics;
3. A top vegetation/soil layer consisting of a minimum 60-cm of soil graded at a slope between 3 and 5 percent with vegetation or an armored top surface.

The installed Compacted Clay Cover is 1.5 m thick which basically matches the recommended EPA design described above. The profile for this cover consists of three layers (Figure 4).

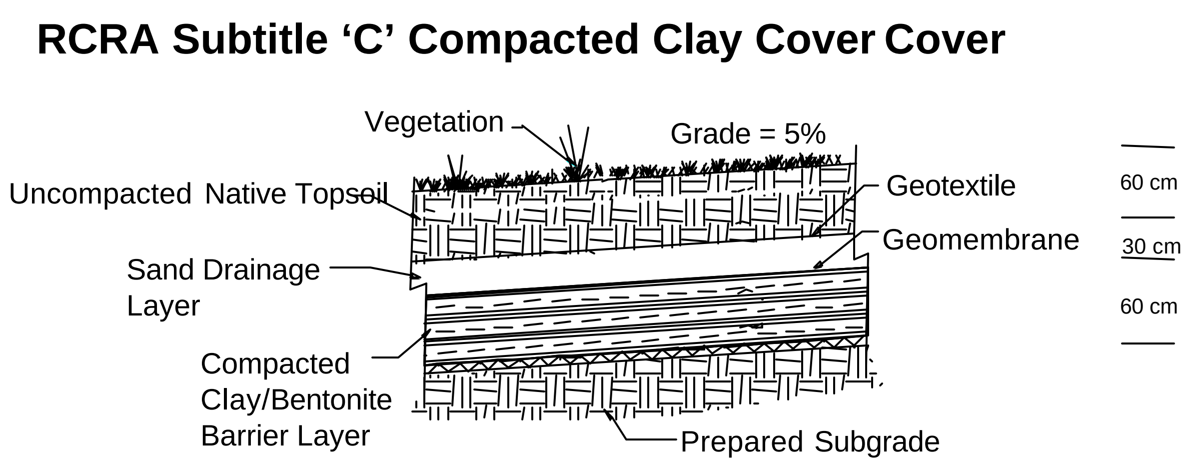

Figure 4. Profile of Baseline Test Cover 2 (Compacted Clay Cover)

The bottom layer is a 60 cm thick compacted soil barrier layer. The native soil required amendment to meet the saturated hydraulic conductivity requirement (maximum of 1 x 10^{-7} cm/sec) for this barrier layer. Laboratory tests determined that a mixture of 6% by weight of sodium bentonite with the native soil compacted ‘wet of optimum’ to a minimum of 98% of maximum dry density per ASTM D698 would be adequate.

A 40 mil linear low density polyethylene (LLDPE) geomembrane was placed directly on the compacted soil barrier layer to create a composite barrier layer (Figure 5). The purpose of this composite barrier layer is to create an impermeable barrier that blocks the infiltration of water. Eight 1-cm^2 defects (puncture holes) were purposely and randomly placed in this geomembrane to be representative of a geomembrane installation with average quality control conditions (Dwyer et al. 1998).

Figure 5. Welding Seams of Geomembrane Panels

The cover’s middle layer is a 30 cm thick drainage layer. The purpose of the drainage layer is to minimize the time any infiltrated water is in contact with the underlying barrier layer by quickly routing water that has passed through the vegetation layer laterally to collection drains. This layer was constructed of sand placed directly on the geomembrane.

The top layer is a 60 cm thick vegetation layer composed of uncompacted soil. This layer’s primary purpose is to provide a medium for vegetation growth, erosion protection, and to protect the underlying layers from freeze/thaw cycles. The vegetative layer allows for storage of infiltrated water that can be removed by evaporation and/or transpired by vegetation.

Alternative Test Covers

All soil used in the construction of the alternative test landfill covers came from on-site cut excavations. Other materials purchased off-site, such as sand and gravel, were common construction materials and readily available (i.e., no exotic grain-size distributions, etc.).

Any and all compaction of soil required by design in the alternative covers was compacted 'dry of optimum' rather than 'wet of optimum' as currently recommended by the EPA for the baseline covers (EPA 1991). Dry-side compaction should result in a compacted barrier soil that is less susceptible to desiccation cracking. Dry-side compaction also made construction easier and therefore less expensive and should provide more soil water storage capability than wet-side storage due to the lower initial degree of saturation.

Alternative Test Cover 1 (Landfill 2) is a Geosynthetic Clay Liner (GCL) Cover (Figure 6) identical to the traditional Compacted Clay Cover, with the exception that the expensive (Dwyer 1998) and problematic (Dwyer 2000) clay barrier layer was replaced with a manufactured sheet known as a GCL installed in its place. All other aspects of the cover were identical to those in Baseline Test Cover 2. The overall thickness of this cover as-built was 90 cm. The cover's component layers from bottom to top is the barrier layer (the GCL membrane covered with a geomembrane that comprises the composite barrier layer), 30 cm sand drainage layer, geotextile filter fabric, and 60 cm vegetation soil layer, respectively. The installed geomembrane also had eight 1-cm^2 randomly placed defects in it similar to those inflicted on the Compacted Clay Cover's geomembrane.

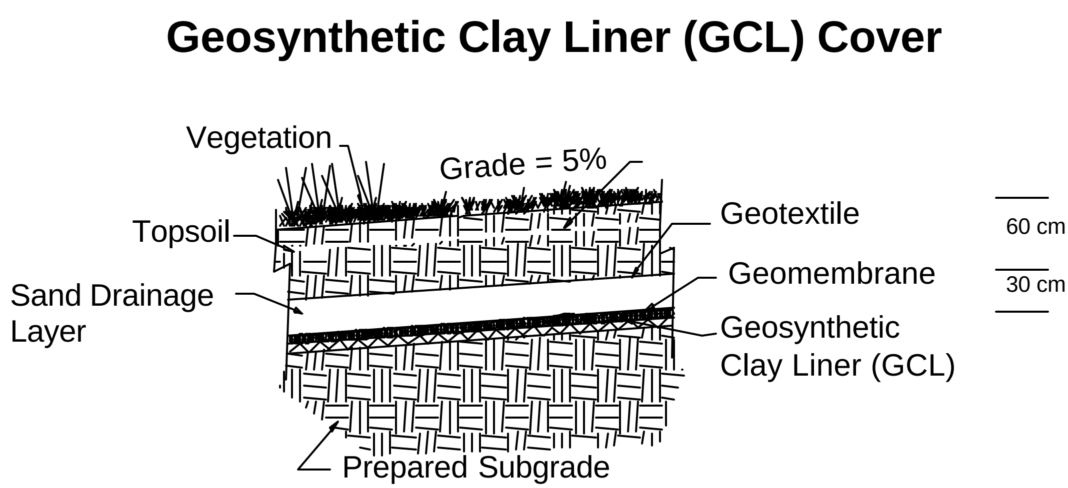

Figure 6. Profile of Alternative Test Cover 1 (GCL Cover)

The GCL installed is a product manufactured by Claymax. It consists of two non-woven fabrics that sandwich a thin layer of bentonite (Figure 7). The delivered-saturated hydraulic conductivity of the GCL per the manufacturer (Claymax 1995) was specified as 5 x 10^{-9} cm/sec.

Figure 7. GCL Installation

Alternative Test Cover 2 (Landfill 4) is a Capillary Barrier. This cover system consists of four primary layers from bottom to top: (1) a lower drainage layer; (2) a barrier soil layer; (3) an upper drainage layer; and (4) a topsoil layer (Figure 8). The barrier soil layer and lower drainage layer comprise the capillary barrier. The lower drainage layer is composed of 30 cm of washed concrete sand.

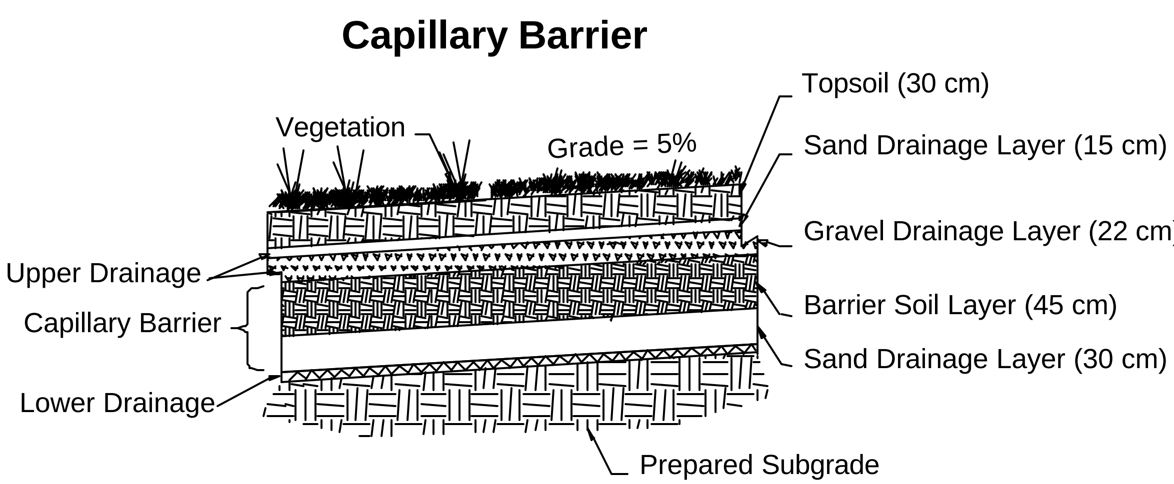

Figure 8. Profile of Alternative Test Cover 2 (Capillary Barrier)

Figure 9. Capillary Barrier Installation

The 45 cm barrier soil layer was installed directly on the sand (Figure 9). The upper drainage layers were placed over the barrier soil layer. This upper drainage layer consists of two materials containing 22 cm of clean pea gravel and 15 cm of washed concrete sand. Finally, a 30 cm thick layer of topsoil was placed on the sand.

Alternative Test Cover 3 (Landfill 5) is another capillary barrier system referred to as the Anisotropic Barrier that is designed to limit the downward movement of water while encouraging the lateral movement of water. This cover is composed of a layering of capillary barriers.

The cover system contains four layers: (1) a top vegetation layer; (2) a cover soil layer; (3) an interface layer; and (4) a sublayer (Figure 10). The vegetation layer is 15 cm thick. It is comprised of a mixture of local topsoil and pea-gravel. The gravel to soil mixture ratio by weight was 0.25 (25%). The gravel was added to assist in minimizing surface erosion due to surface runoff. This layer encourages evapotranspiration, allows for vegetation growth, and reduced surface erosion. The cover native soil layer is 60 cm thick. Its function is to allow for water storage and eventual evapotranspiration and to serve as a rooting medium. The interface layer is 15 cm of fine sand that serves as a filter between the overlying soil and the underlying gravel, and serves as a drainage layer to laterally divert water to collection areas that has percolated through the cover soil. The sublayer is 15 cm of pea-gravel. The native soil overlying the sand layer create one capillary barrier while the sand overlying the pea gravel creates a second capillary break.

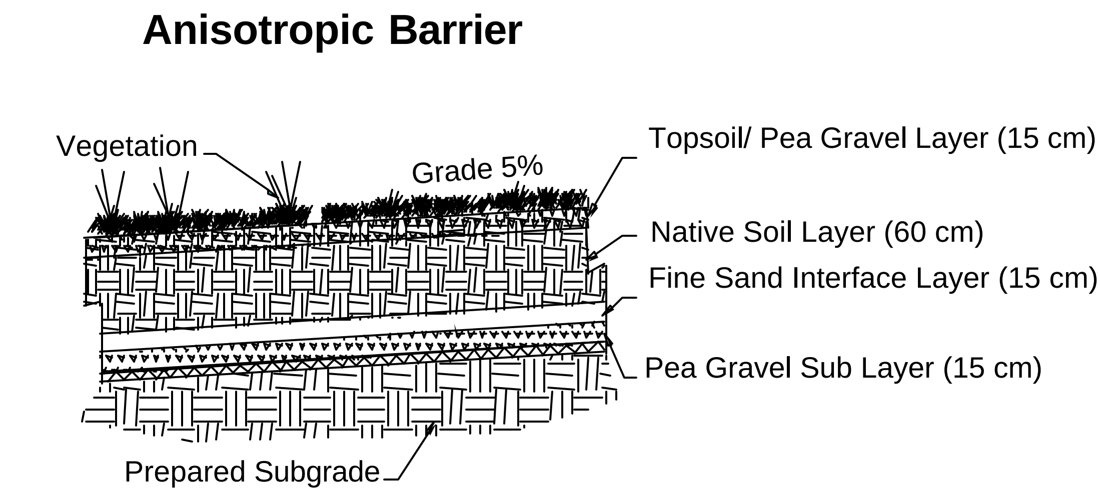

Figure 10. Profile of Alternative Test Cover 3 (Anisotropic Barrier)

Alternative Test Cover 4 (Landfill 6) is referred to as an Evapotranspiration (ET) Cover (Figure 11). The ET Cover consists of a single, vegetated soil layer constructed to represent an optimum mix of soil texture, soil thickness, and vegetation cover.

The installed test cover is a 105 cm thick monolithic soil cover. The bottom 90 cm of native soil was compacted while the top 15 cm of topsoil was loosely placed. The soil allows for water storage, which combined with the vegetation, is designed to optimize evapotranspiration.

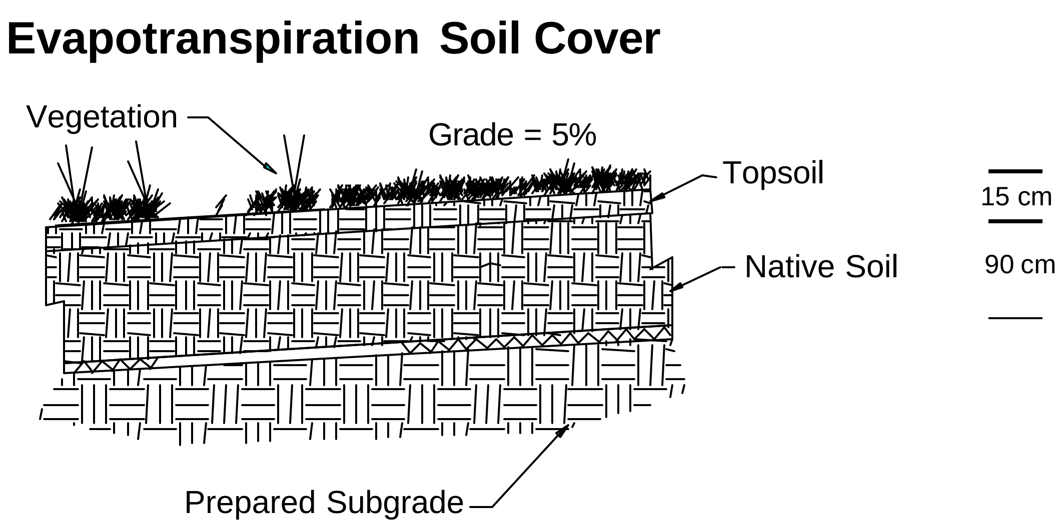

Figure 11. Profile of Alternative Cover 4 (ET Cover)

A thin gravel veneer (2 to 4 cm) was placed on the surface after the cover was seeded. The objective of the gravel veneer was to enhance the vegetation establishment and minimize erosion.

Figure 12. Compacting Soil in ET Cover

After the covers were constructed, they were drill-seeded with native rangeland vegetation. The seed mix (Table 1) was chosen based on an acceptable native vegetation that would provide an adequate coverage during both warm and cool growing seasons.

Table 1. Seed Mix for Test Covers

	Desired Establishment [1] **(% of total vegetation)**	**Quantity in Mixture** [2] **(lbs./acre)**
Warm Season Grasses:		
Bouteloua gracillis (Blue Grama)	20	1.0
Hilaria jamesii (Galleta)	10	3.0
Sporabolis cyptandrus (Sand Dropseed)	50	0.5
Cool Season Grasses:		
Oryzopsis hymenoides (Indian Ricegrass)	10	3.0
Stipa comata (Needle & Thread)	10	4.0

(1) Approximate percentage of total species present in number of plants per given area.

(2) Note that differences in weight among the various species can result in large differences in the mass ratio (lbs/acre) of seed required in the seed mixture.

PERFORMANCE MONITORING AND INSTRUMENTATION

Passive testing consists of daily on-site observations to validate system performance and to correct problems as they potentially develop. Continuous data is being obtained on soil moisture status, percolation and interflow, runoff and erosion, precipitation, wind speed and direction, relative humidity, solar radiation, air and soil temperatures. Periodic measurements on vegetation cover, biomass, leaf area index, and species composition are also obtained (Wolters et al. 2000).

Active testing includes the addition of supplemental precipitation to hydrologically stress the different cover systems. Water applied using the sprinkler system is tested for rate and uniformity of application. All water is distributed through electronically controlled flowmeters where quantities discharged are controlled and measured. This system has the capability to apply water quantities that simulate worst case precipitation events. All other measurements under this precipitation regime are the same as those described above for passive monitoring.

The water balance equation being used is:

$$\mathbf{E = P - I - R - D - \Delta S;}$$

where: precipitation plus applied water if any (P), surface runoff (R), lateral drainage (D), evapotranspiration (E), soil water storage (S), and percolation or infiltration (I) are the six water balance variables. With the exception of 'E', quantities for all other variables in the water balance equation are being obtained with the monitoring systems. Evapotranspiration is then determined by solving the water balance equation for 'E'. All measurements are made with automated monitoring systems to provide continuous data (Dwyer et al. 1998). Manual backup systems are available for use in case of failure in one or more of the automated measurements systems and/or to verify accuracy of the automated systems.

Soil Moisture: Time Domain Reflectometry (TDR) and an associated data acquisition system (Figure 13 b) is used to provide a continuous record of soil moisture status at various plan locations and depths within each cover profile (Figure 13a). Each TDR probe was individually calibrated to achieve the highest degree of accuracy possible (Lopez et al. 1997). PVC pipes were installed strategically in the covers to be used as ports to allow for the use of frequency domain reflectometry as a backup.

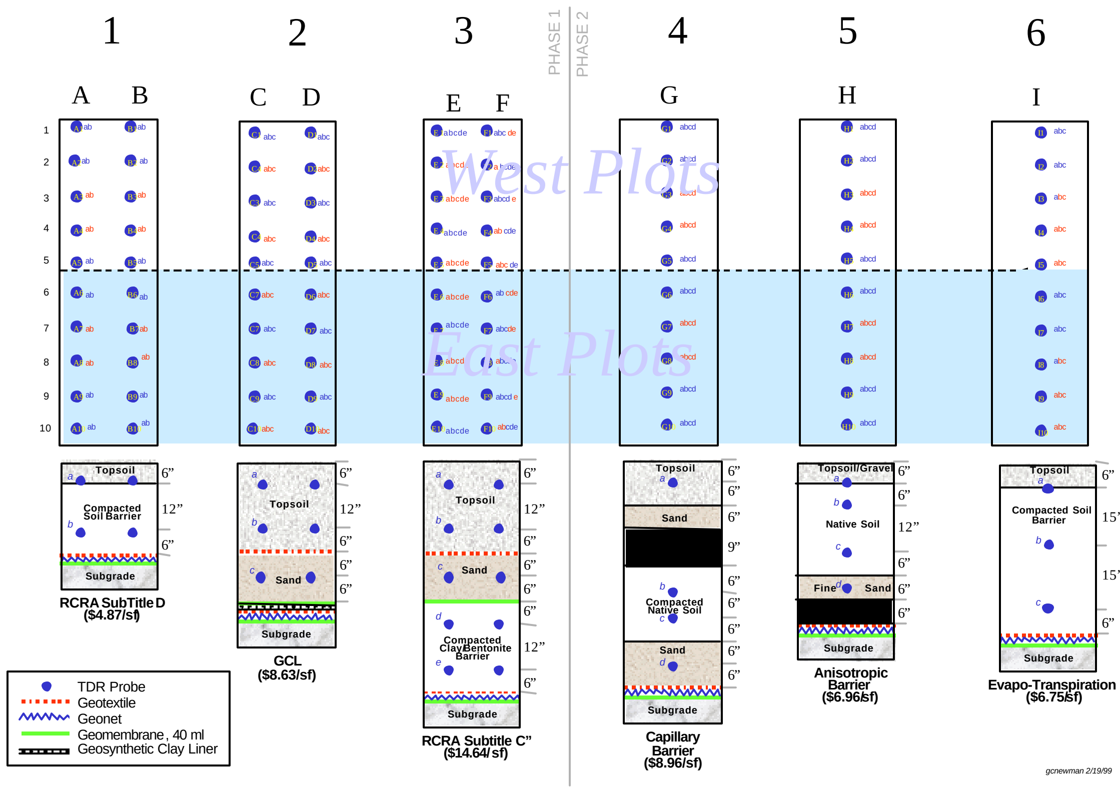

Figure 13a. TDR System Deployment

Figure 13b. TDR Cable Tester and Data Logger

Runoff and Erosion: Runoff and erosion are measured on an event basis. Surface runoff water is collected with a gutter system located at the bottom of each slope component of each cover (Figure 14). The collected water is routed to instrumentation that quantifies the amount and a data acquisition system is linked to the instrumentation to automatically record and store the data.

Figure 14. Surface Water Gutter Collection

Percolation and Interflow: Subsurface flows are measured. Lateral drainage from each drainage layer (GCL Cover and RCRA Subtitle ‘C’ Compacted Clay Cover) is collected using underdrain systems placed at the bottom of each slope component of each cover. The water is routed to instrumentation that quantifies it. The instrumentation is linked to a data acquisition system to continuously record flow events. Percolation through the barrier layer within each cover is collected using a geomembrane under a geonet that routes the water to an underdrain collection system. Both percolation and interflow is routed via drains to the flow monitoring system. Measurement redundancy is built into the system to reduce the probability of losing data because of equipment failure or power loss and to verify correctness of results obtained. All monitoring instrumentation is housed in a shelter (Figure 15).

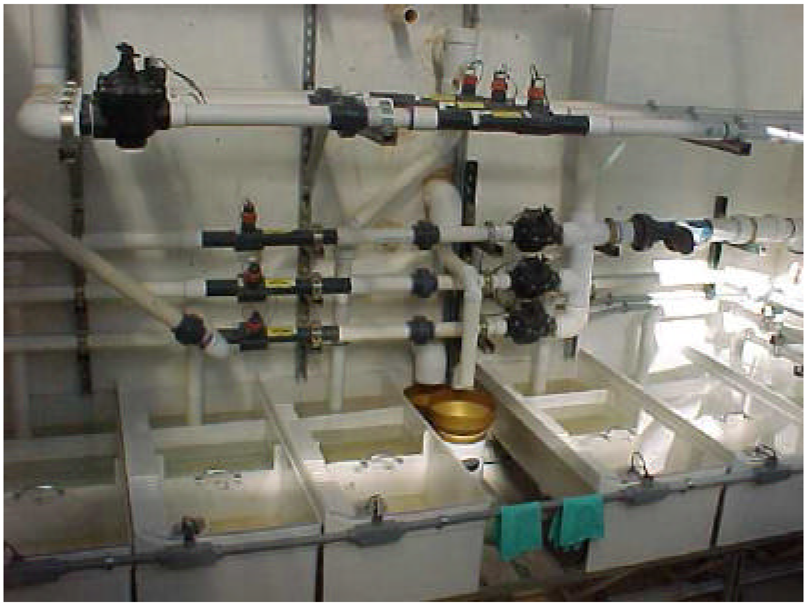

Figure 15. Instrumentation Housed Inside Shelter

Meteorology: A complete weather station (Figure 16) was installed at the ALCD site. Precipitation, air temperature, wind speed and direction, relative humidity, and solar radiation are continuously recorded. The meteorological measurements are made with automated equipment coupled to the data acquisition system.

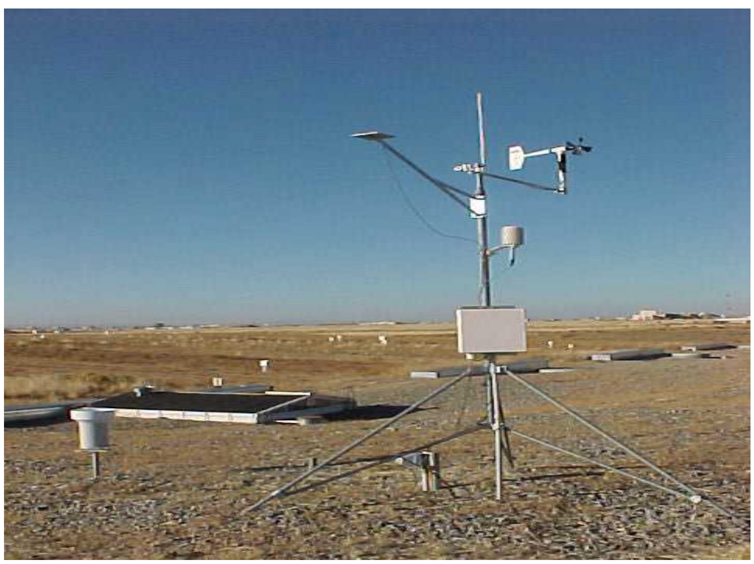

Figure 16. On-Site Weather Station

Vegetation: Attributes of the vegetation on each landfill cover (Wolters et al. 2000) are measured yearly to relate vegetation characteristics to potential changes in erosion and evapotranspiration. Several point frames are used to evaluate total cover, species count and vegetation biomass (Figure 17 a and b). Biomass production is determined by clipping and weighing oven-dried samples collected from subplots within each landfill cover. Species composition is measured using line transects staked within each landfill subplot.

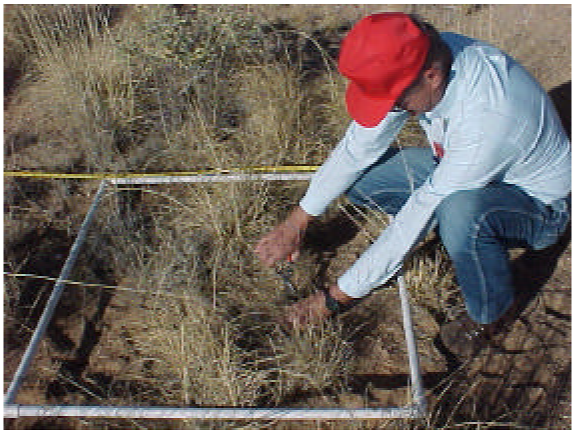

Figure 17a. Vegetation Density Count

Figure 17b. Vegetation Species Count

RESULTS

The data presented in this report is that measured at the ALCD site from May 1997 through June 2000. This data is presented without conclusions because data is still being collected and trends are still being developed. This demonstration is a long-term demonstration (minimum five years post construction) and it would be premature to draw conclusions at this time with a minimum of two more years of monitoring to be completed. Conclusions will be presented in a final report of the ALCD project findings at the conclusion of the study, currently estimated as September 30, 2002.

The measured percolation and precipitation data collected to date is presented below in tabular format. The first year of monitoring (1997) was a relatively wet year. The precipitation values listed in Table 2 include the periods May through Dec of 1997 and January through June of 2000 as well as all of 1998 and 1999. The last two years (1999 and 2000) have been extremely dry years. The precipitation values are also presented in graphical format in Appendix A.

Table 2. Measured Precipitation Values at the ALCD Site

Precipitation Totals	
Year	**Volume (liters)**
1997 (May 1 - Dec 31)	154,585
1998	169,048
1999	130,400
2000 (Jan 1 - Jun 25)	28,151

The measured percolation values for each landfill test cover are presented in Table 3. Again, measurements for 1997 are for May through December and measurements for 2000 are for January through June only. The percolation data was converted into a respective flux rate (mm/year) for each cover (Table 4). Percolation vs. precipitation is also graphically presented in Appendix B.

Table 3. Measured Percolation Values of Test Covers at the ALCD Site

Year	Percolation Totals (l)					
	Subtitle D	**GCL**	**Subtitle C**	**Capillary Barrier**	**Anisotropic Barrier**	**ET**
1997 (May 1 - Dec 31)	3974	564	46	607	57	84
1998	2764	210	169	456	77	243
1999	1740	2401	20	472	155	6
2000 (Jan 1 - Jun 25)	0	0	0	0.02	0	0
Total	8478	3175	235	1535	289	333

Table 4. Flux Rate Values of Test Covers at the ALCD Site

Year	Flux rates (mm/year)					
	Subtitle D	GCL	Subtitle C	Capillary Barrier	Anisotropic Barrier	ET
1997 (May 1 - Dec 31)	10.62	1.51	0.12	1.62	0.15	0.22
1998	4.96	0.38	0.30	0.82	0.14	0.44
1999	3.12	4.31	0.04	0.85	0.28	0.01
2000 (Jan 1 - Jun 25)	0.00	0.00	0.00	0.00	0.00	0.00
Average	4.82	1.81	0.13	0.87	0.16	0.19

Estimates of each cover efficiency for each cover are listed in Table 5. In essence, the efficiency value quantifies how "efficient" the covers prevent precipitation moisture from infiltrating into the underlying waste.

Table 5. Efficiency Values of Test Covers at the ALCD Site

Year	Efficiency = (1 - Percolation/Precipitation) * 100%					
	Subtitle D	GCL	Subtitle C	Capillary Barrier	Anisotropic Barrier	ET
1997	97.4294	99.6349	99.9702	99.6076	99.9630	99.9456
1998	98.3651	99.8758	99.9000	99.7302	99.9546	99.8560
1999	98.6653	98.1584	99.9850	99.6381	99.8809	99.9954
2000	100.000	100.000	100.0000	100.000	100.000	100.000
Average	98.6149	99.4173	99.9638	99.7440	99.9496	99.9492

The presentation of past data from the ALCD has generally centered on the test covers measured percolation. A stakeholder has specifically requested that all water balance data measured with respect to the ET Cover be presented in this report. This request has been granted. Consequently, all water balance data measured on the ET Cover, as well as similar data on all covers, is included. Water balance data collected on the ET Cover include percolation, surface runoff, and soil moisture. There is no drainage layer in the ET Cover therefore the lateral drainage parameter does not exist for this cover. Bear in mind that the vegetation on the covers built during Phase I was established one year earlier that the vegetation on the covers built during Phase II. Slight variations in surface runoff and soil moisture can be noticed due to the differences in vegetation growth on the covers pertaining to the two phases, as well as the different surface treatments associated with these covers. In general, however, the data collected to date is good and clearly reveals the differences in water balance activity within the six landfill covers. Surface runoff versus precipitation is graphically presented in Appendix C. Soil Moisture versus precipitation is graphically presented in Appendix D. Finally, ET versus precipitation for the six covers is graphically presented in Appendix E.

DISCUSSION

Without regulatory and public acceptance, promising environmental technologies have little chance for successful implementation. Also very important to the acceptance of new environmental technologies are their costs. A study performed by the University of North Dakota (Wentz 1989) concluded that the deciding factors affecting which hazardous waste management technology should be used for a particular site included from most important to least important: 1) government regulations, 2) economics, 3) public relations, and 4) process/technology. The ALCD project has been committed from the start towards regulatory and public acceptance of the project and the technologies presented in the demonstration. Furthermore, the design criteria for the alternative cover designs required that the new designs be less expensive to construct than the traditional designs.

Because permits can be difficult to obtain and there has been only minimal work conducted to promote alternative covers based on regional environmental requirements, many design engineers are reluctant to deviate far from conventional designs.

The project's test cover designs were initially sent out for review first by a group of technical peers who were independent of the project and deemed industry experts. This review helped ensure the technical validity of the proposed cover designs and associated data acquisition system. Comments were gathered from the reviewers and incorporated into the cover and test designs.

The revised test plan was then sent to regulatory representatives from environmental departments throughout most of the western states. The test plan was also sent out to representatives from several EPA regional offices and comments from this review were also incorporated into the design package.

Lawmakers and regulators have become more sensitive to special interest group concerns and are consequently encouraging the inclusion of these groups in the permitting process. The ALCD has received the endorsement of a committee from a western states' and federal government initiative to accelerate and improve cleanup of federal lands. This initiative originated in 1992, when the Western Governors Association, the Secretaries of Defense, Energy, and Interior, and the Administration of the Environmental Protection Agency formed a federal advisory committee to cooperate on the cleanup of federal waste management sites in the region. This committee, known as the Committee to Develop On-Site Innovative Technologies (DOIT Committee), has sought the guidance of key players to help identify, test, and evaluate more cooperative approaches to deploying promising innovative waste remediation and management technologies in order to clean up federal waste sites in an expeditious and cost-effective manner.

The DOIT Committee's primary goal with regard to the ALCD is to 1) assist with the eventual acceptance of new technologies that come from the demonstration and 2) inclusion of landfill permitting in an interstate reciprocity program the Committee is attempting to finalize.

Finally, another review process included sending out a general overview of the demonstration to members of the DOIT Committee as well as special interest groups identified by the DOIT

Committee. These special interest groups included representatives from the Sierra Club, Indian tribes, government agencies, neighborhood associations, local businesses, engineering firms, and politicians. Over 1000 groups received the information. Reply comments were forwarded through the Western Governors Association for consideration. The majority of these comments centered on questions rather than comments and on praise for getting them involved early in the process. Periodic progress meetings were held with representatives of some of the special interest groups, Western Governors Association, regulatory agencies, New Mexico State Legislature, and Sandia National Laboratories.

EXPECTED BENEFITS

The ALCD project is expected to provide performance and cost data for landfill cover components and systems that are more applicable to western climatic conditions than currently recommended prescriptive designs. A direct comparison between conventional and alternative designs will be available. The "active" testing activities will permit data to be collected under extreme and accelerated conditions. This information will allow those responsible for the development of landfill cover design guidance to have a defensible basis for the transition from designs suited for the eastern United States to those more suited to the western United States.

The probable outcome of this demonstration is the acceptance of alternative cover designs that are significantly less costly, but more effective than conventional designs. Given the thousands of acres of buried waste sites to be covered, the payoff from this demonstration may be savings on the order of billions of dollars to taxpayers.

ACKNOWLEDGMENTS

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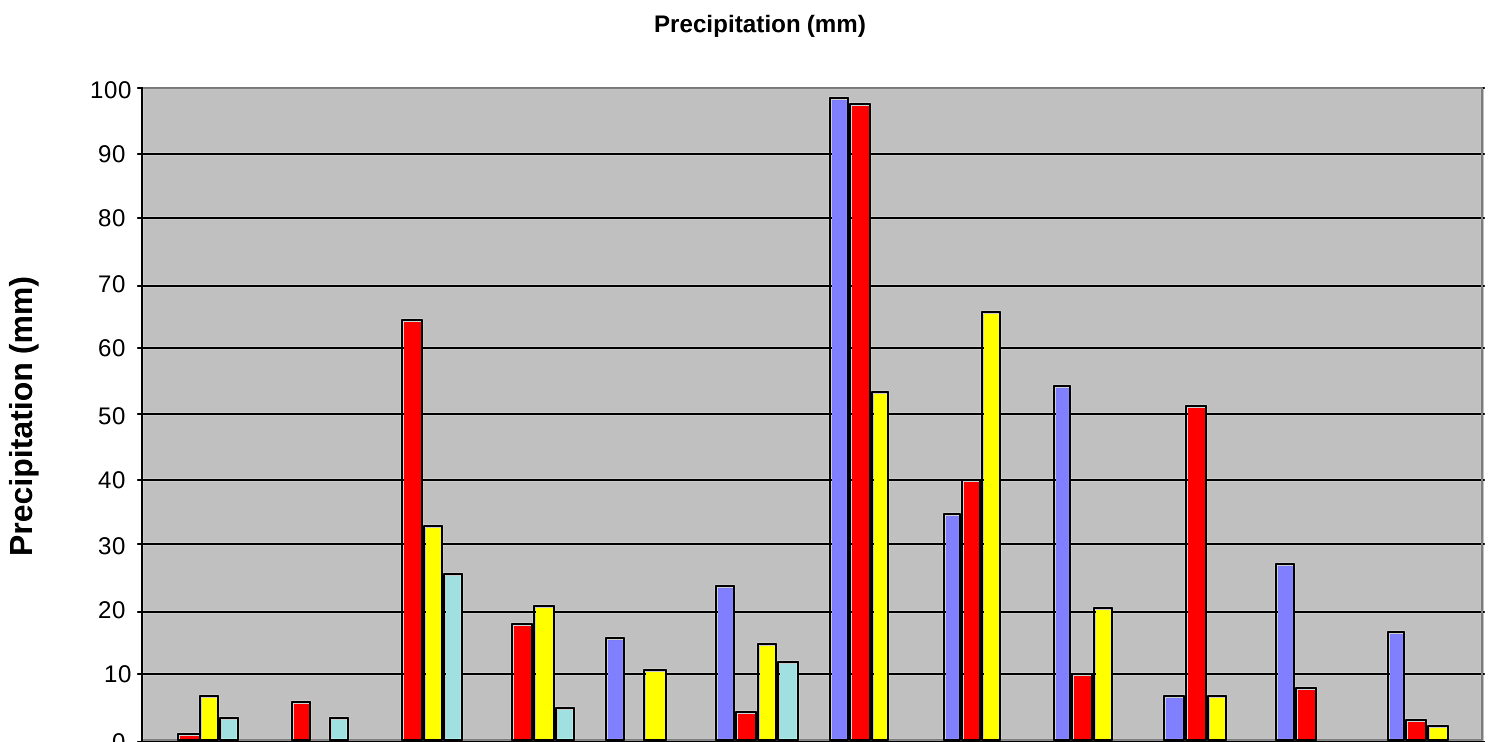
Appendix A

Precipitation Measured at the ALCD Site



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997					15.49	24.13	98.80	34.29	54.32	6.86	26.92	16.5
1998	1.02	5.59	64.52	17.78	0.00	4.32	97.53	39.88	10.16	51.3	8.13	3.05
1999	6.60	0.00	32.77	20.57	10.92	14.73	53.34	66.04	20.32	6.60	0.00	2.03
2000	3.81	3.81	25.79	5.08	0.00	12.02	0.00	0.00	0.00	0.00	0.00	0.00

Figure A-1. Measured Precipitation at ALCD, May 1997 to June 2000

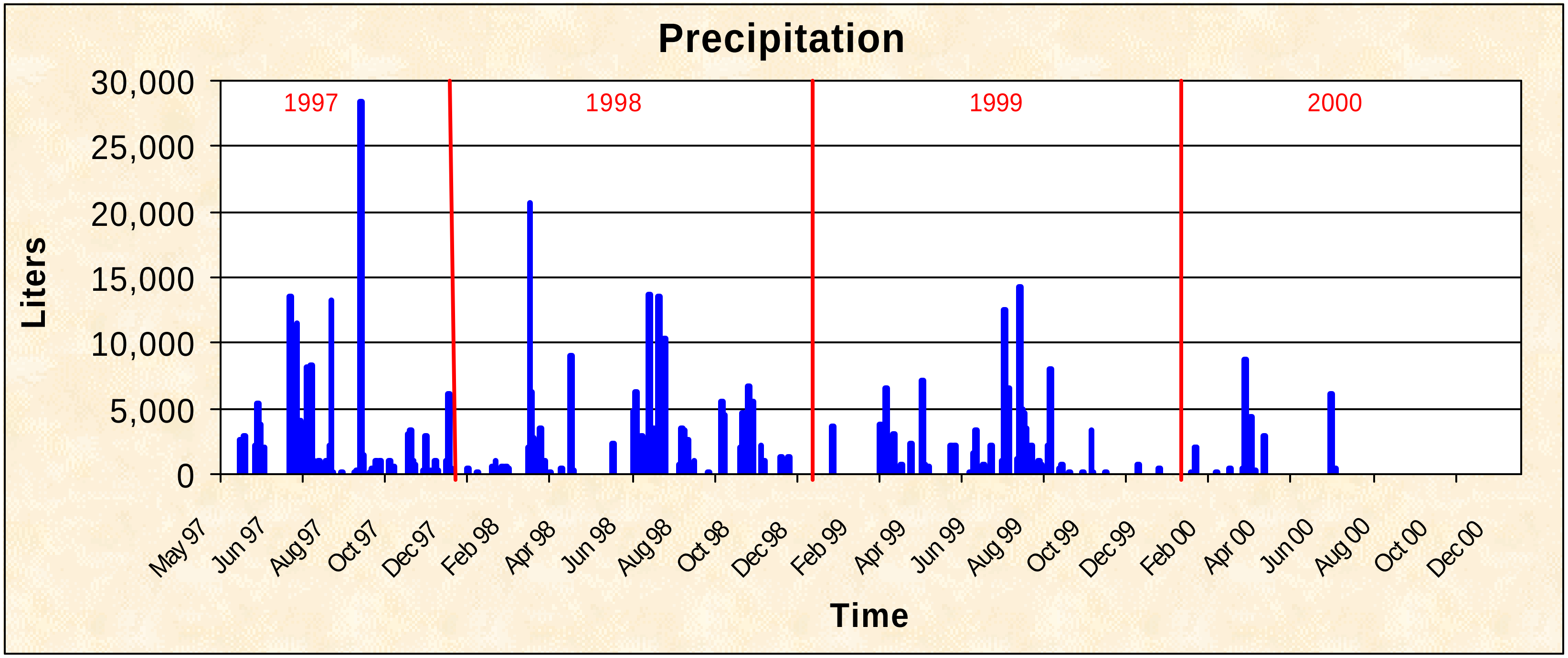
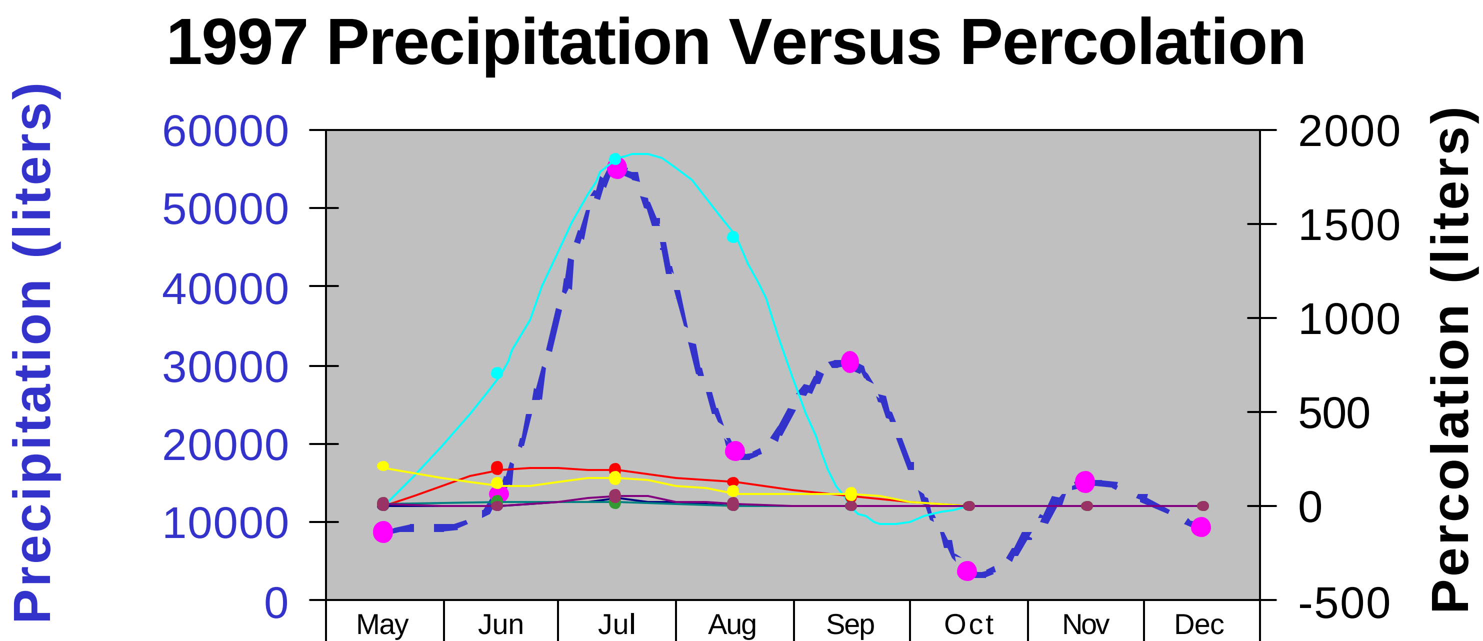


Figure A-2. Precipitation at ALCD Site

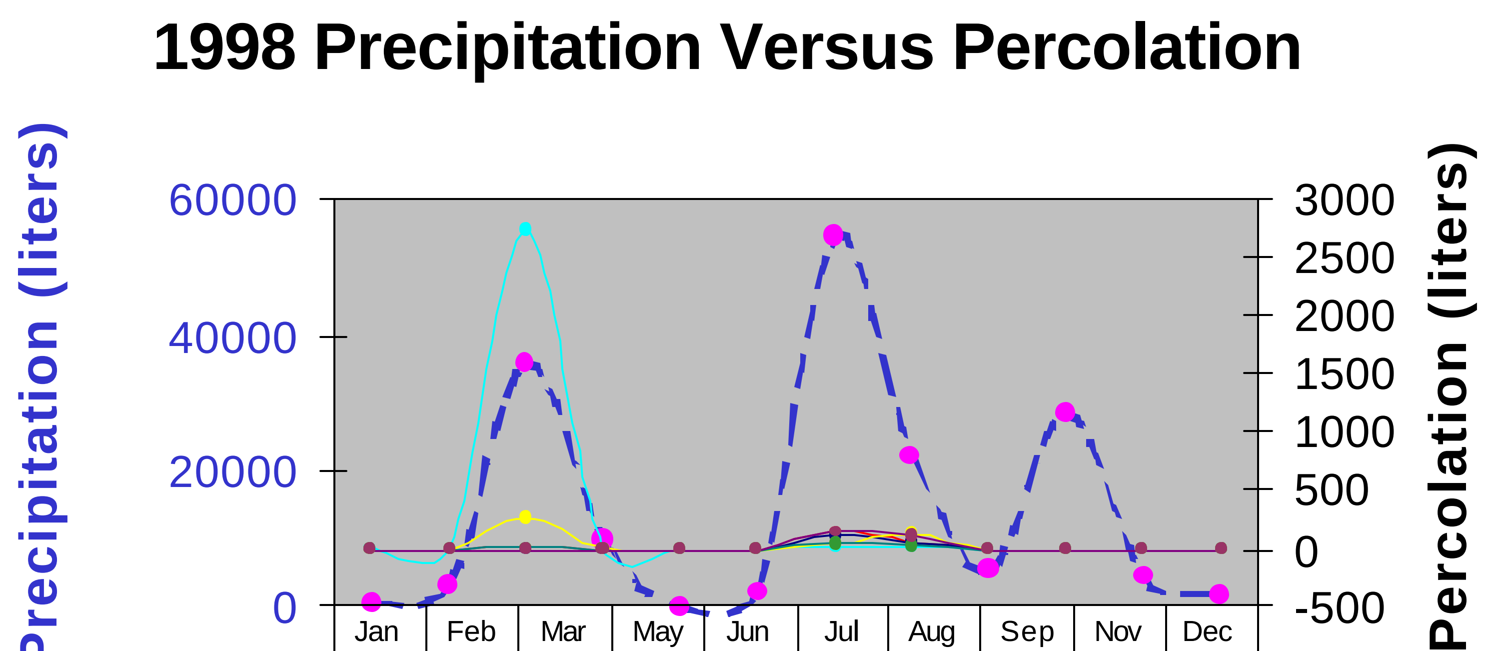
Appendix B

Precipitation Versus Percolation



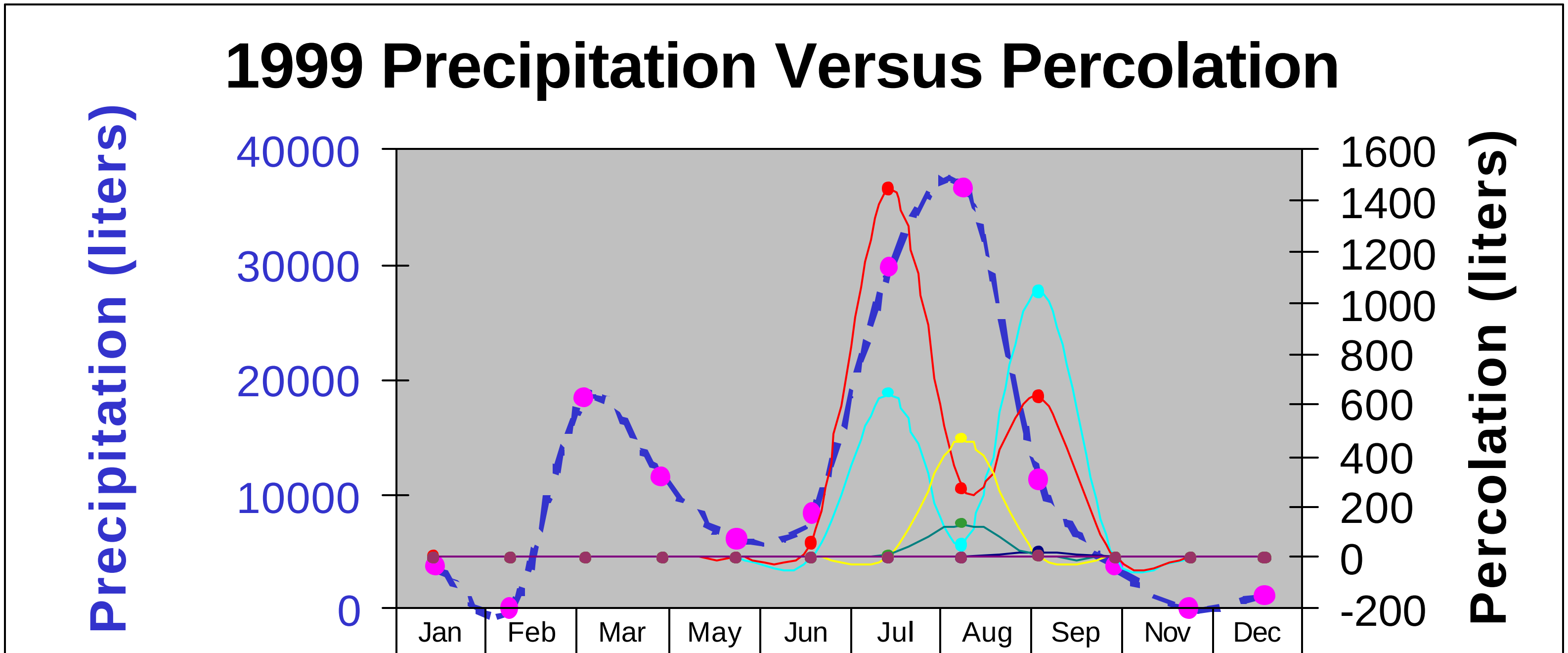
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precip	8637	13451	55075	19115	30277	3823	15008	9201
Perc LF1	0.0	699.3	1842.9	1428.0	1.8	0.9	0.7	0.2
Perc LF2	0.3	200.8	188.3	122.3	51.5	0.2	0.4	0.7
Perc LF3	0.0	0.1	45.5	0.3	0.2	0.0	0.0	0.0
Perc LF4	210.6	111.1	142.7	76.7	64.0	0.1	0.5	0.8
Perc LF5	8.3	24.1	24.2	0.0	0.0	0.0	0.2	0.5
Perc LF6	6.2	0.0	57.0	15.1	4.9	0.1	0.3	0.5

Figure B-1. 1997 Precipitation Versus Percolation



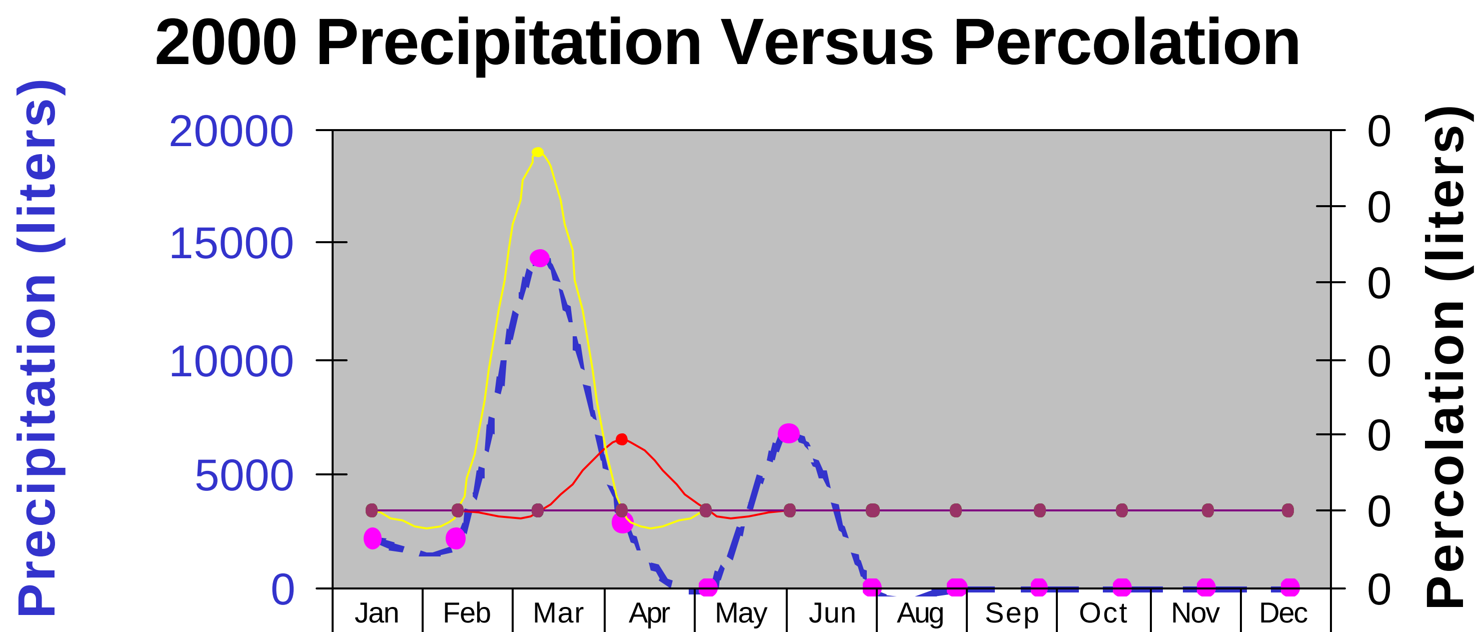
	Jan	Feb	Mar	May	Jun	Jul	Aug	Sep	Nov	Dec
Precip	566	3115	35962	0	2407	54366	22228	5663	4531	1699
Perc LF1	1.4	0.0	2751.7	0.0	0.0	3.2	7.3	0.0	0.1	0.0
Perc LF2	0.3	0.1	7.0	0.0	1.2	139.0	62.0	0.0	0.2	0.0
Perc LF3	0.0	0.0	0.0	0.0	0.0	106.5	62.5	0.0	0.0	0.0
Perc LF4	0.4	0.2	260.2	0.0	0.0	47.0	134.7	0.0	0.0	0.0
Perc LF5	0.3	0.1	4.8	0.0	0.0	37.6	34.0	0.0	0.0	0.0
Perc LF6	0.2	0.2	0.1	0.0	0.0	137.4	105.0	0.0	0.2	0.0

Figure B-2. 1998 Precipitation Versus Percolation



	Jan	Feb	Mar	May	Jun	Jul	Aug	Sep	Nov	Dec
Precip	3681	0	18264	6088	8212	29734	36812	11327	0	1133
Perc LF1	0.0	0.0	0.0	0.0	0.0	646.1	48.2	1046.0	0.0	0.0
Perc LF2	0.8	0.0	0.0	0.0	53.7	1447.1	265.2	634.6	0.0	0.0
Perc LF3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.6	0.0	0.0
Perc LF4	0.0	0.0	0.0	0.0	0.0	6.5	463.4	1.9	0.0	0.0
Perc LF5	0.0	0.0	0.0	0.0	0.0	13.5	135.2	6.5	0.0	0.0
Perc LF6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	0.0	0.0

Figure B-3. 1999 Precipitation Versus Percolation

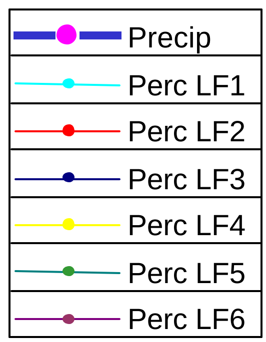


	Jan	Feb	Mar	Apr	May	Jun	Aug	Sep	Oct	Nov	Dec
Precip	2124	2124	14374	2832	0	6698	0	0	0	0	0
Perc LF1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0
Perc LF2	0.000	0.000	0.000	0.005	0.000	0.000	0.000	0.0	0.0	0.0	0.0
Perc LF3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0
Perc LF4	0.000	0.000	0.024	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0
Perc LF5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0
Perc LF6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.0	0.0	0.0	0.0

Figure B-4. 2000 Precipitation Versus Percolation

Appendix C

Precipitation Versus Runoff



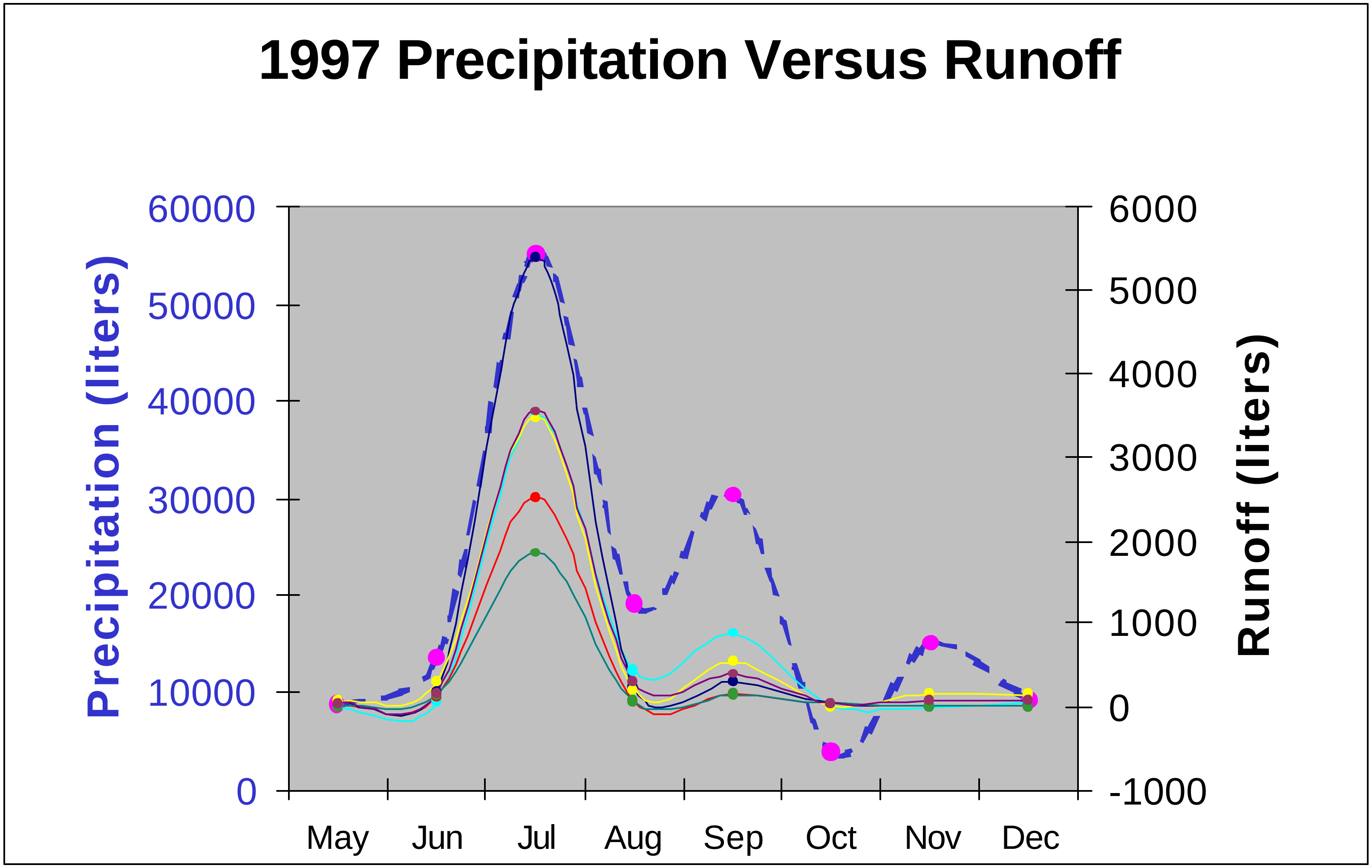


Figure C-1. 1997 Precipitation Versus Runoff

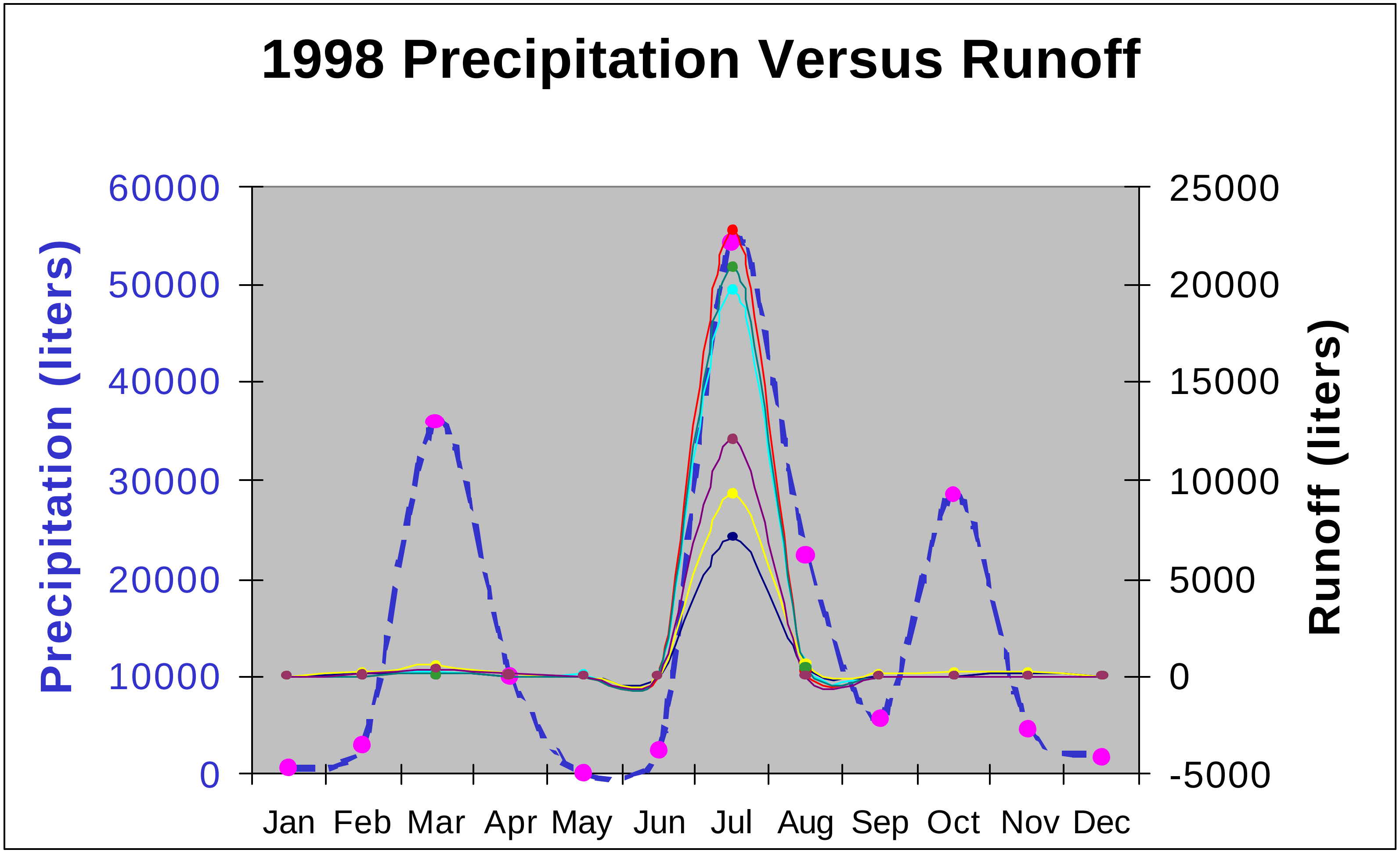


Figure C-2. 1998 Precipitation Versus Runoff

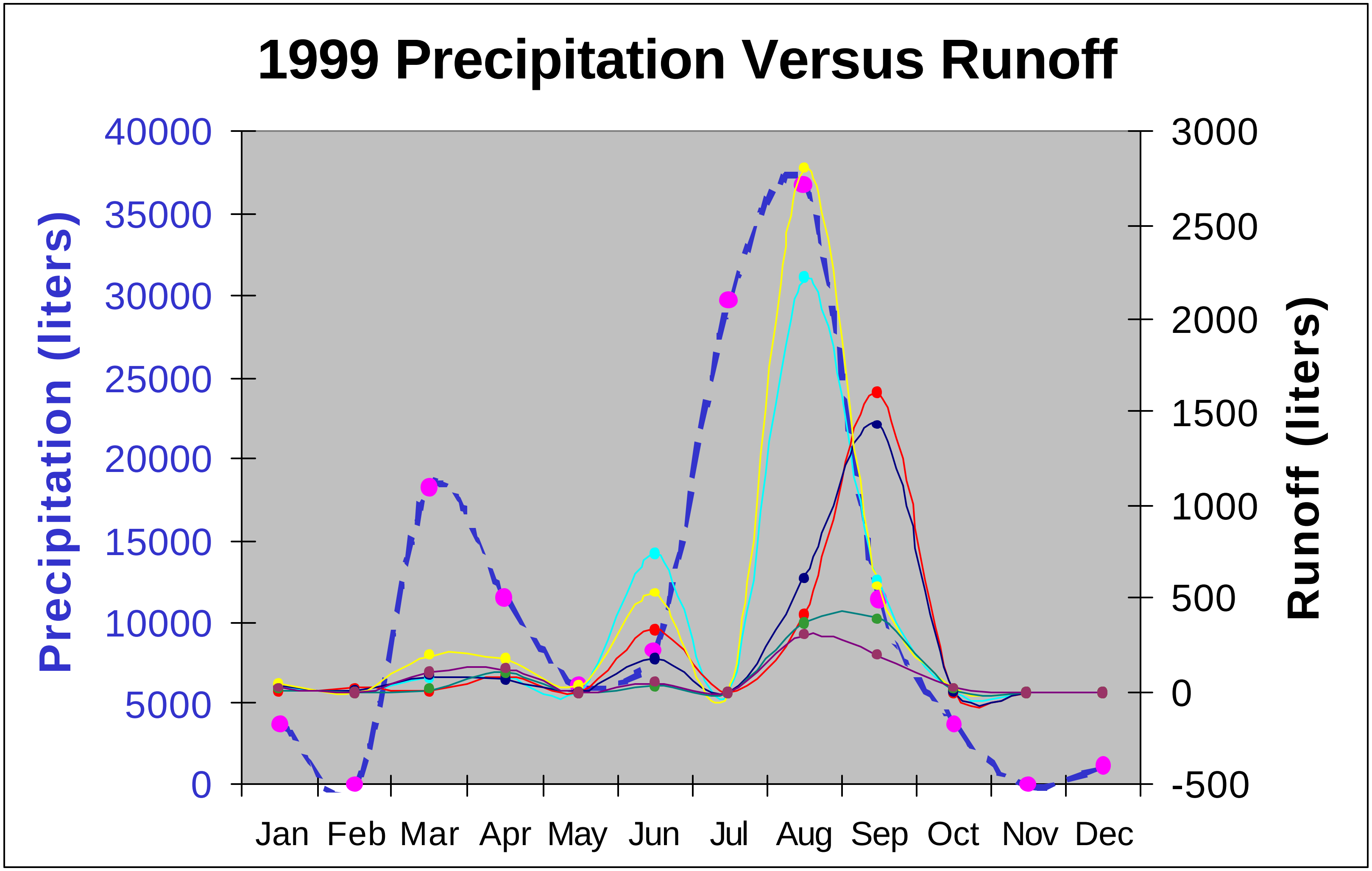


Figure C-3. 1999 Precipitation Versus Runoff

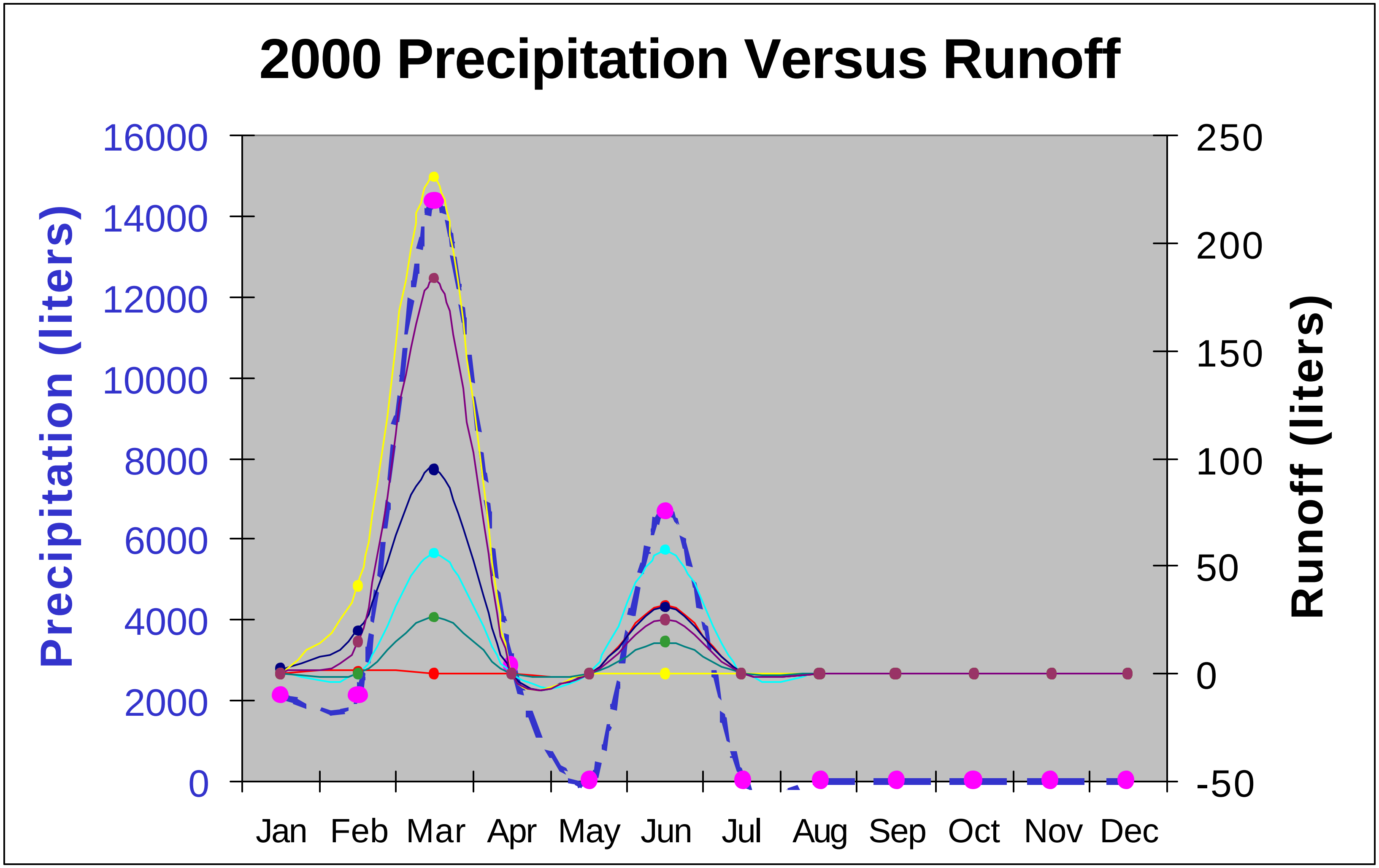


Figure C-4. 2000 Precipitation Versus Runoff

Appendix D

Precipitation Versus Soil Moisture

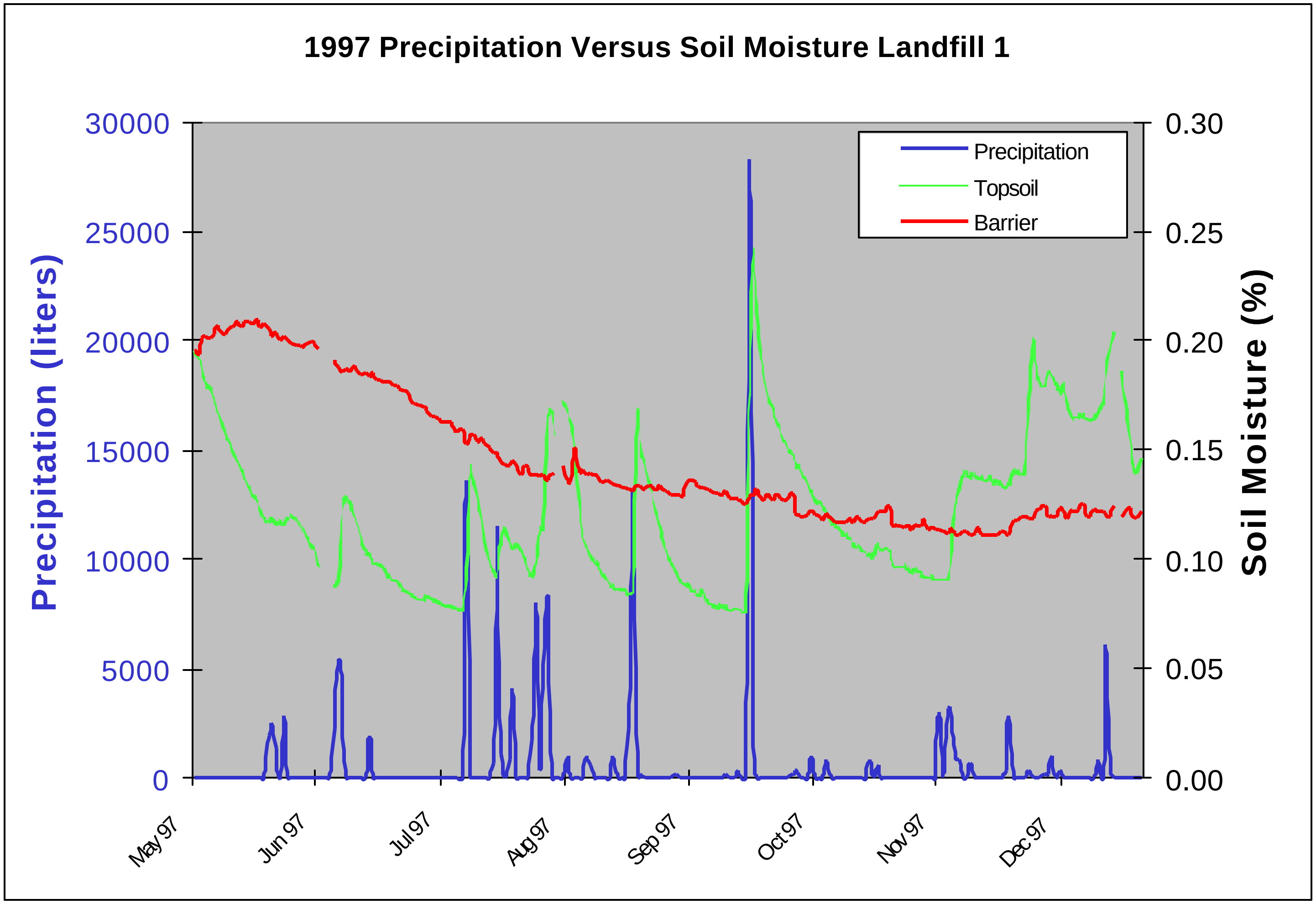


Figure D-1. 1997 Precipitation Versus Soil Moisture Landfill 1

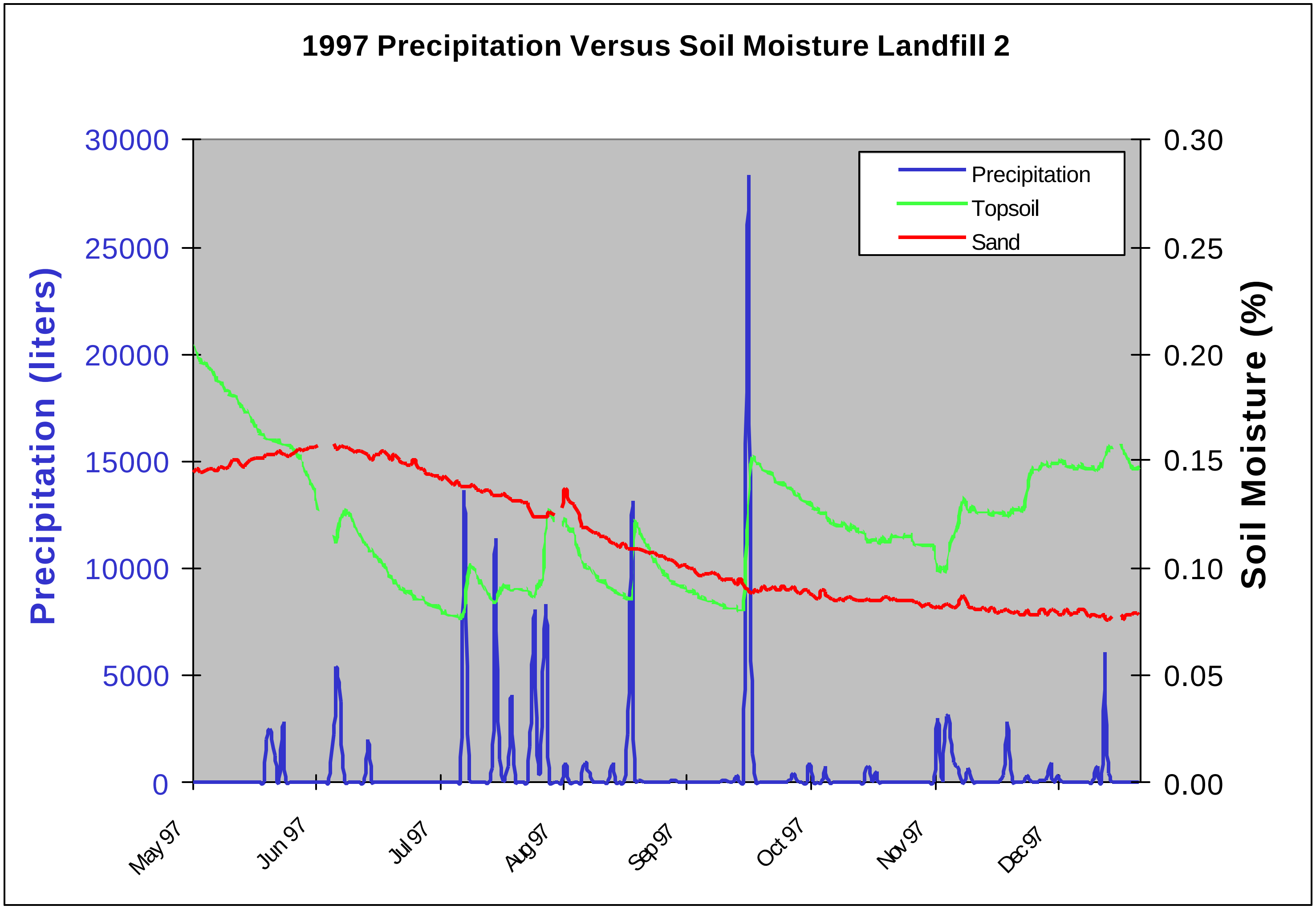


Figure D-2. 1997 Precipitation Versus Soil Moisture Landfill 2

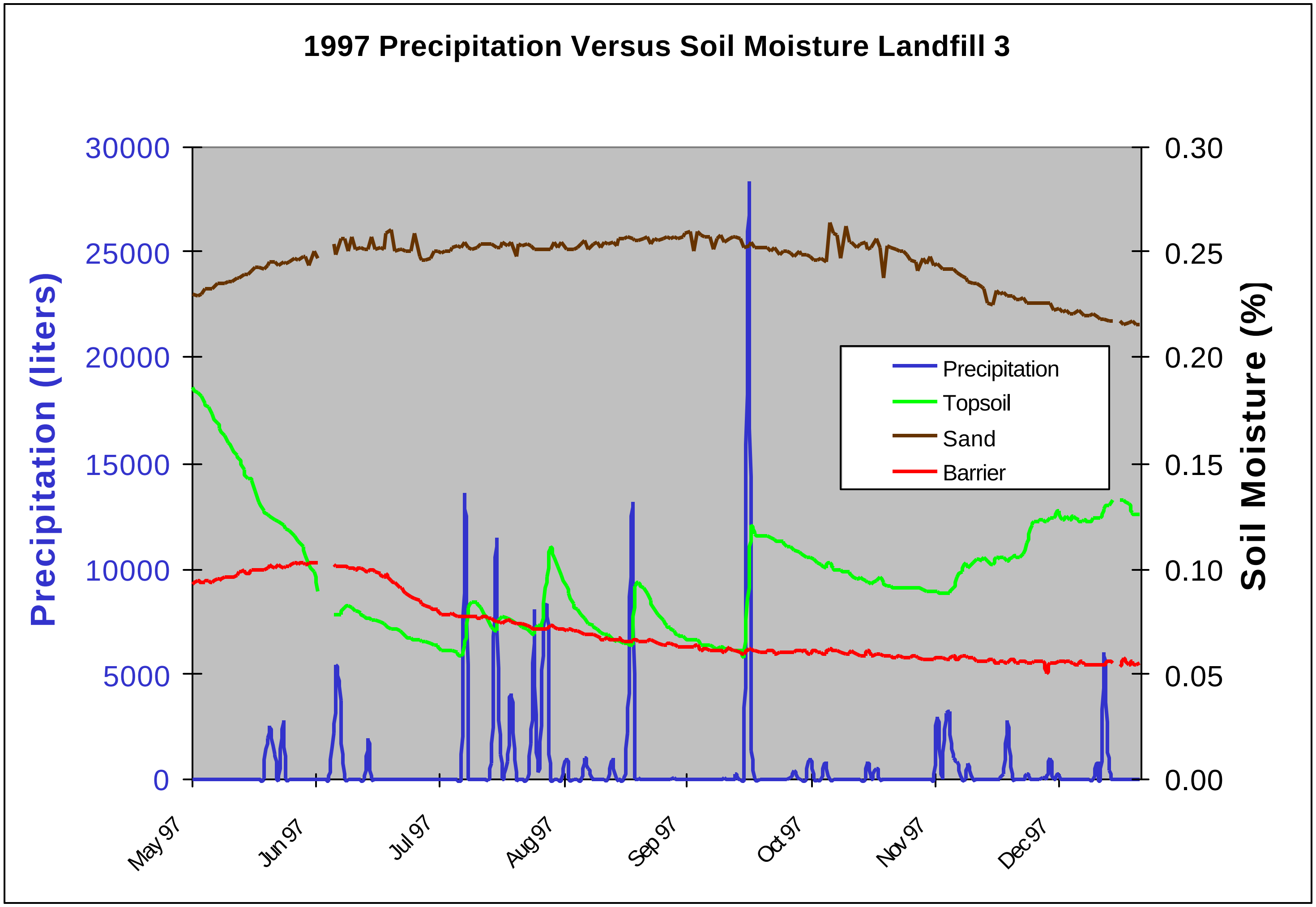


Figure D-3. 1997 Precipitation Versus Soil Moisture Landfill 3

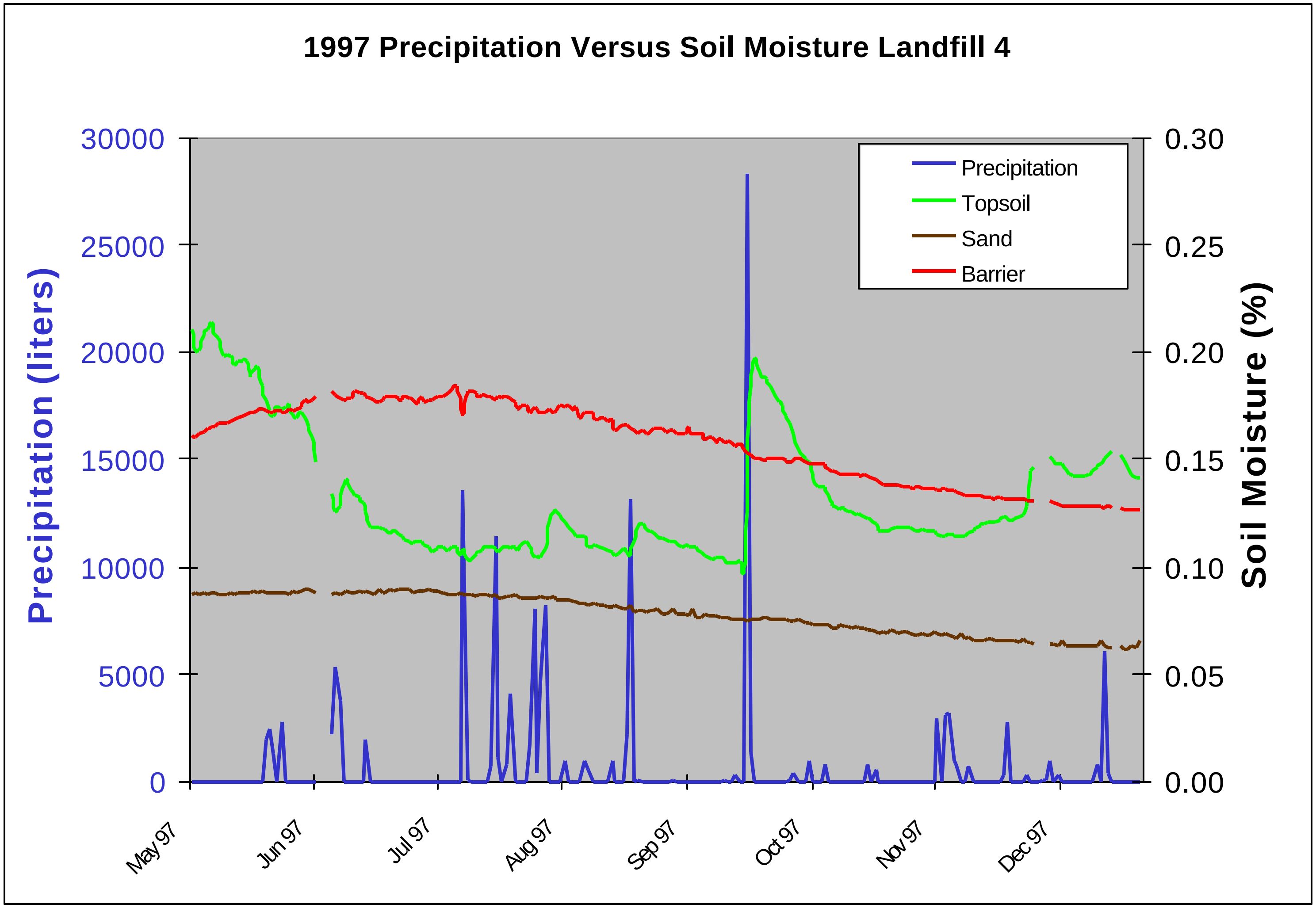


Figure D-4. 1997 Precipitation Versus Soil Moisture Landfill 4

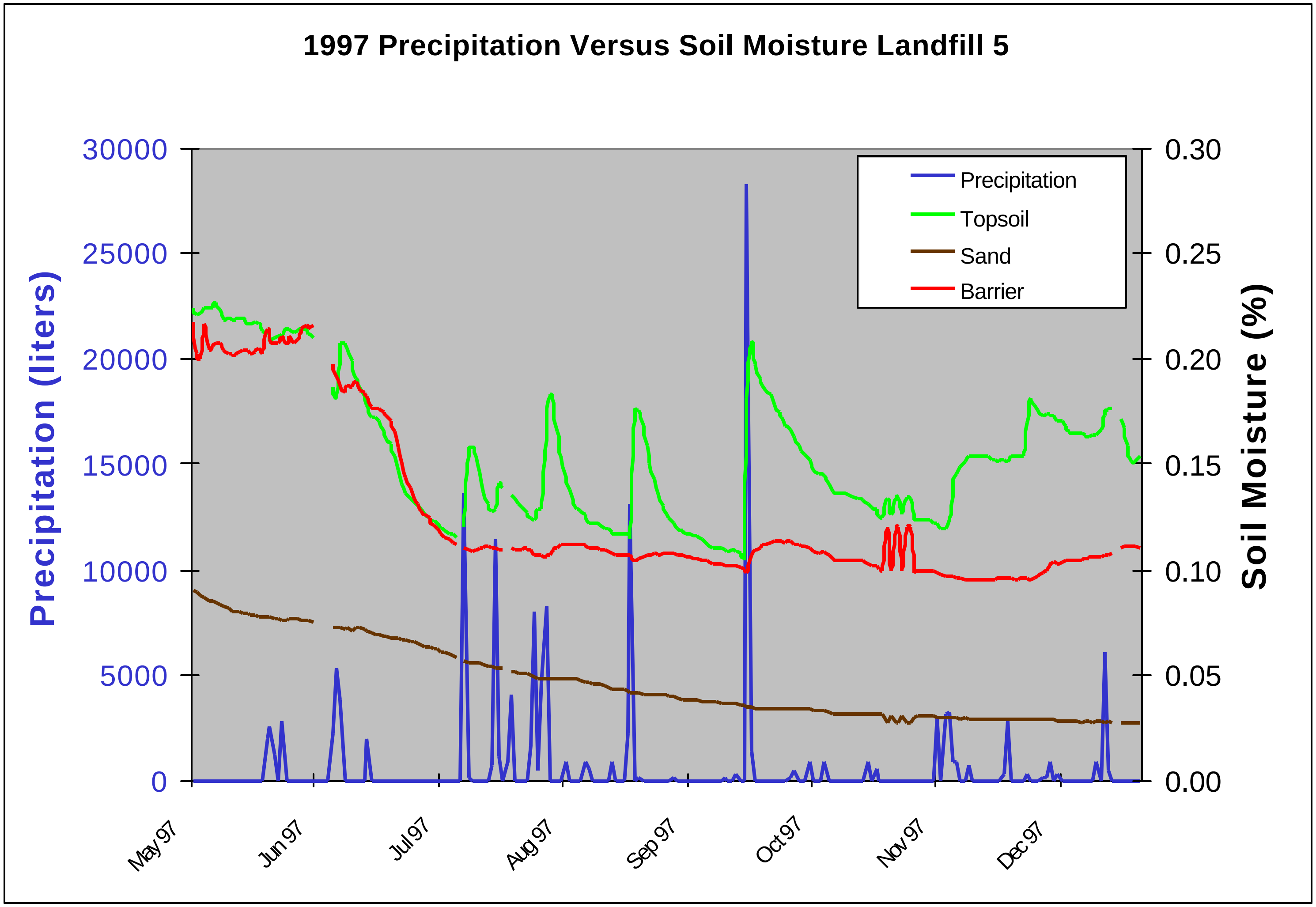


Figure D-5. 1997 Precipitation Versus Soil Moisture Landfill 5

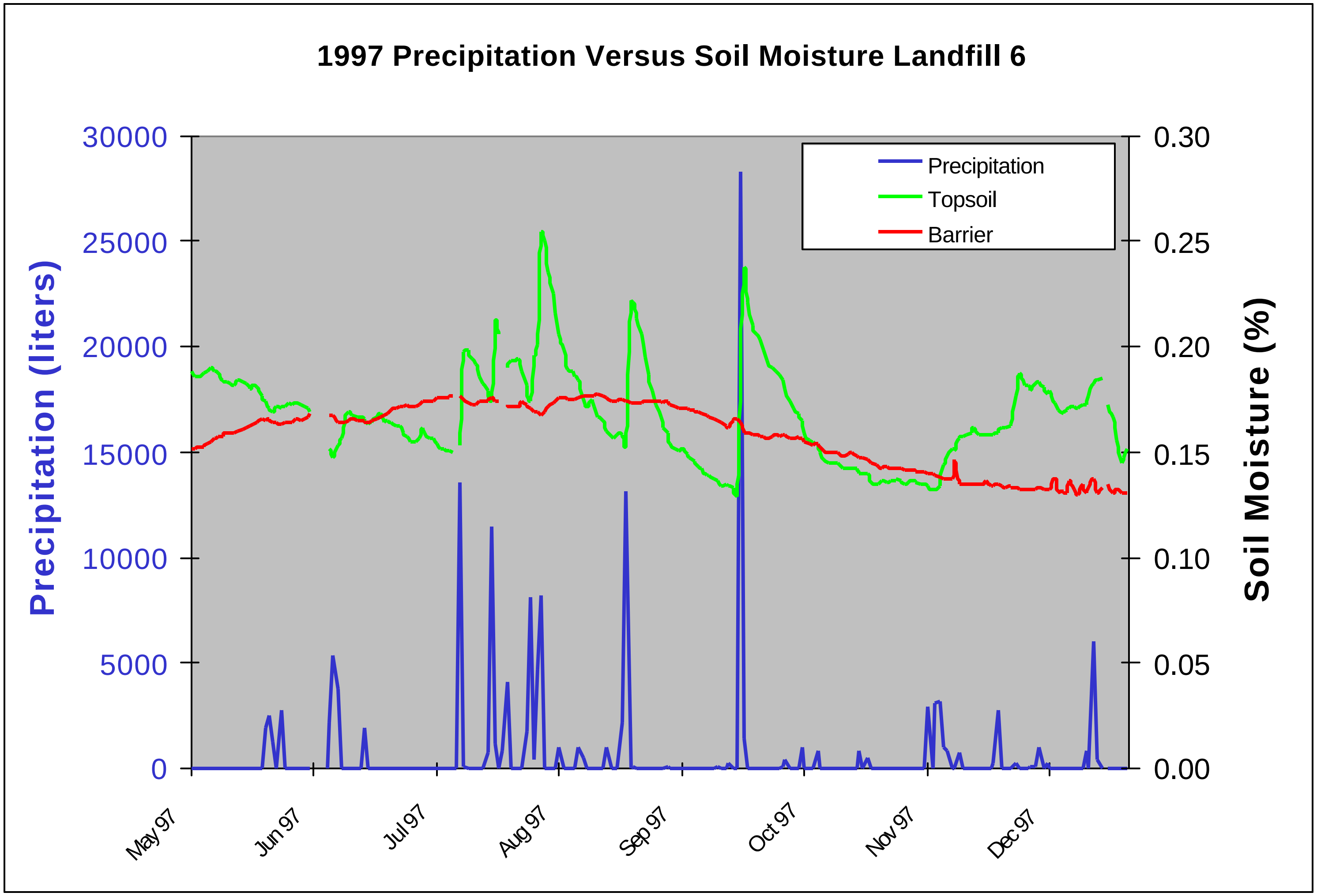


Figure D-6. 1997 Precipitation Versus Soil Moisture Landfill 6

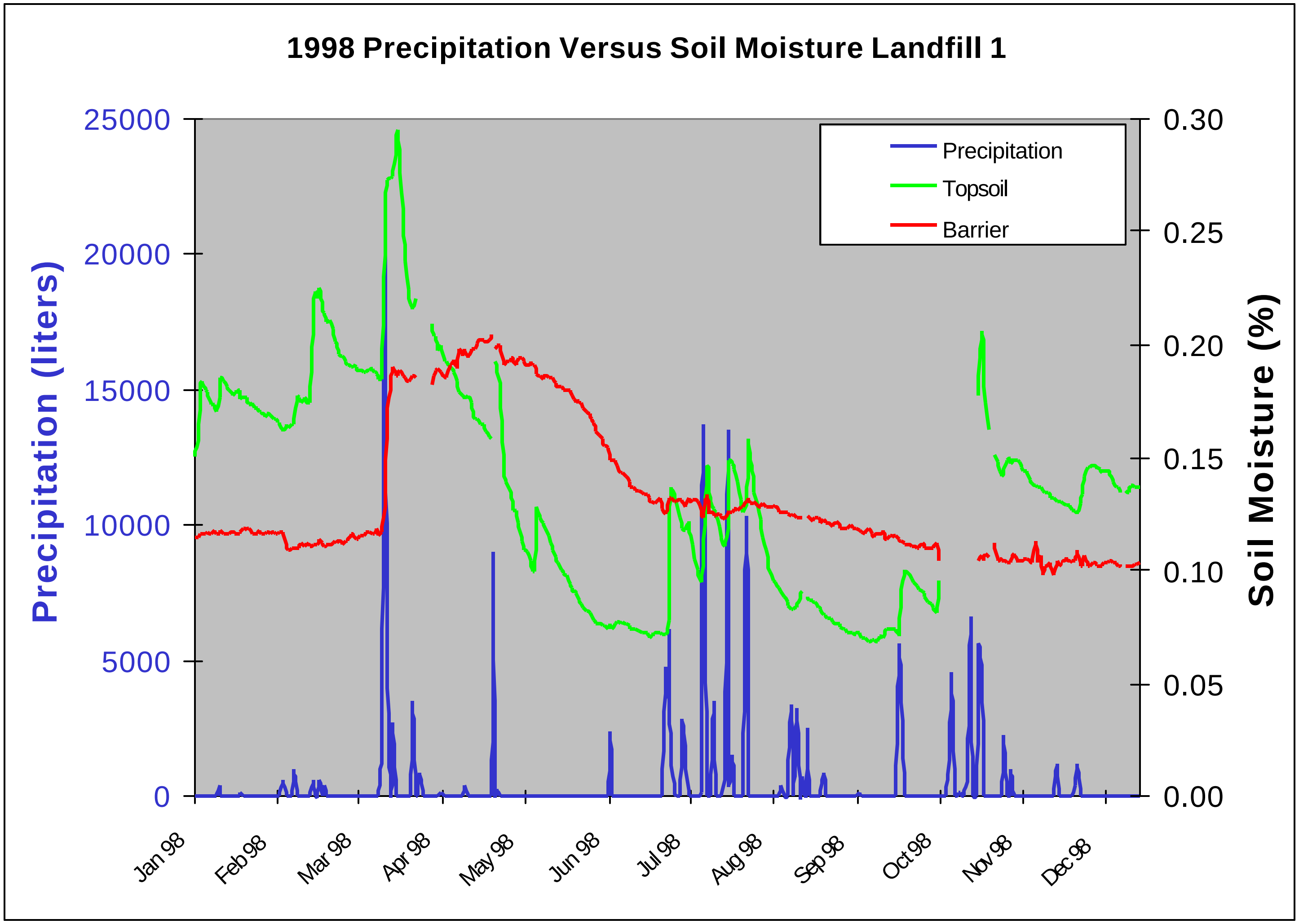


Figure D-7. 1998 Precipitation Versus Soil Moisture Landfill 1

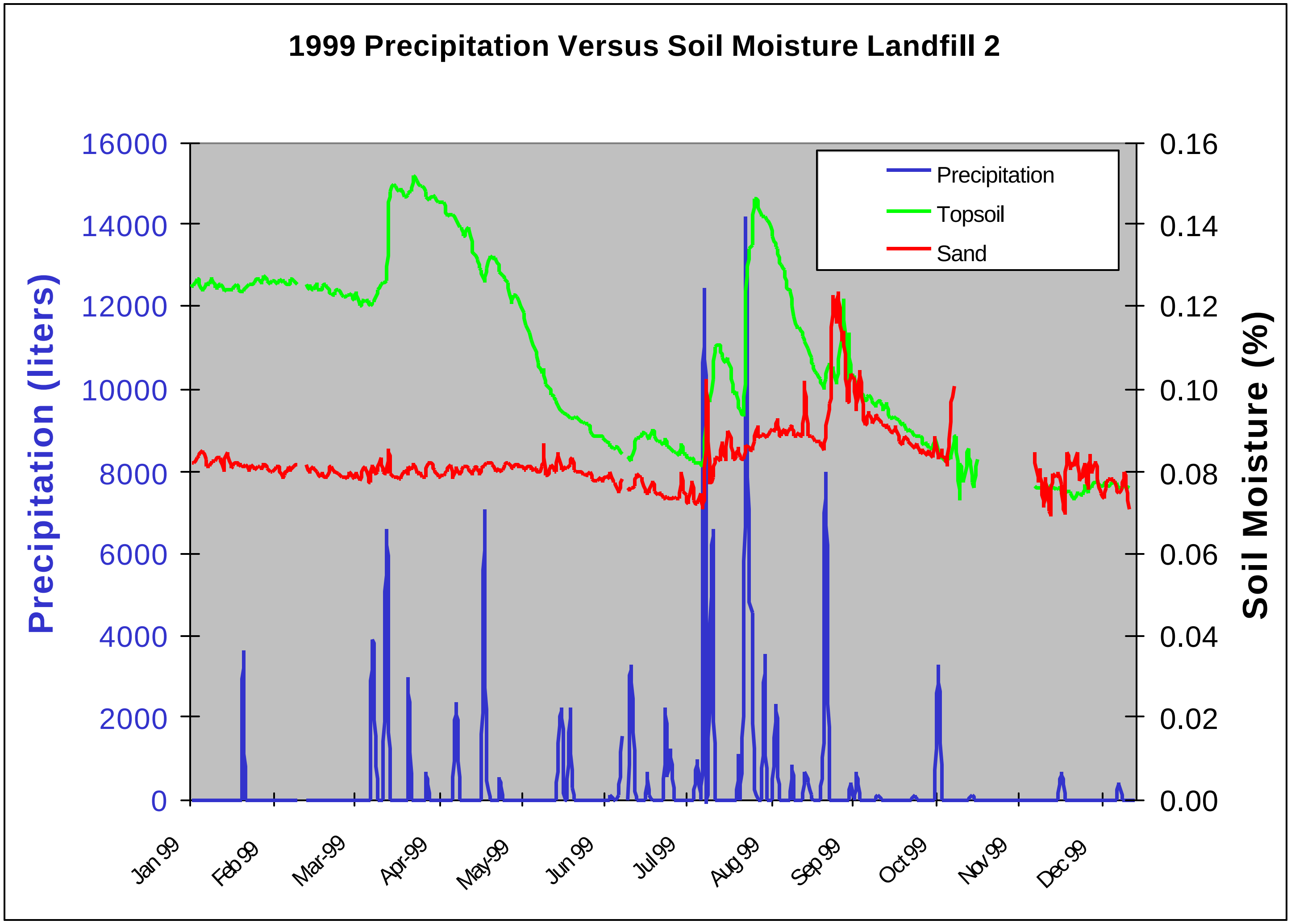


Figure D-8. 1998 Precipitation Versus Soil Moisture Landfill 2

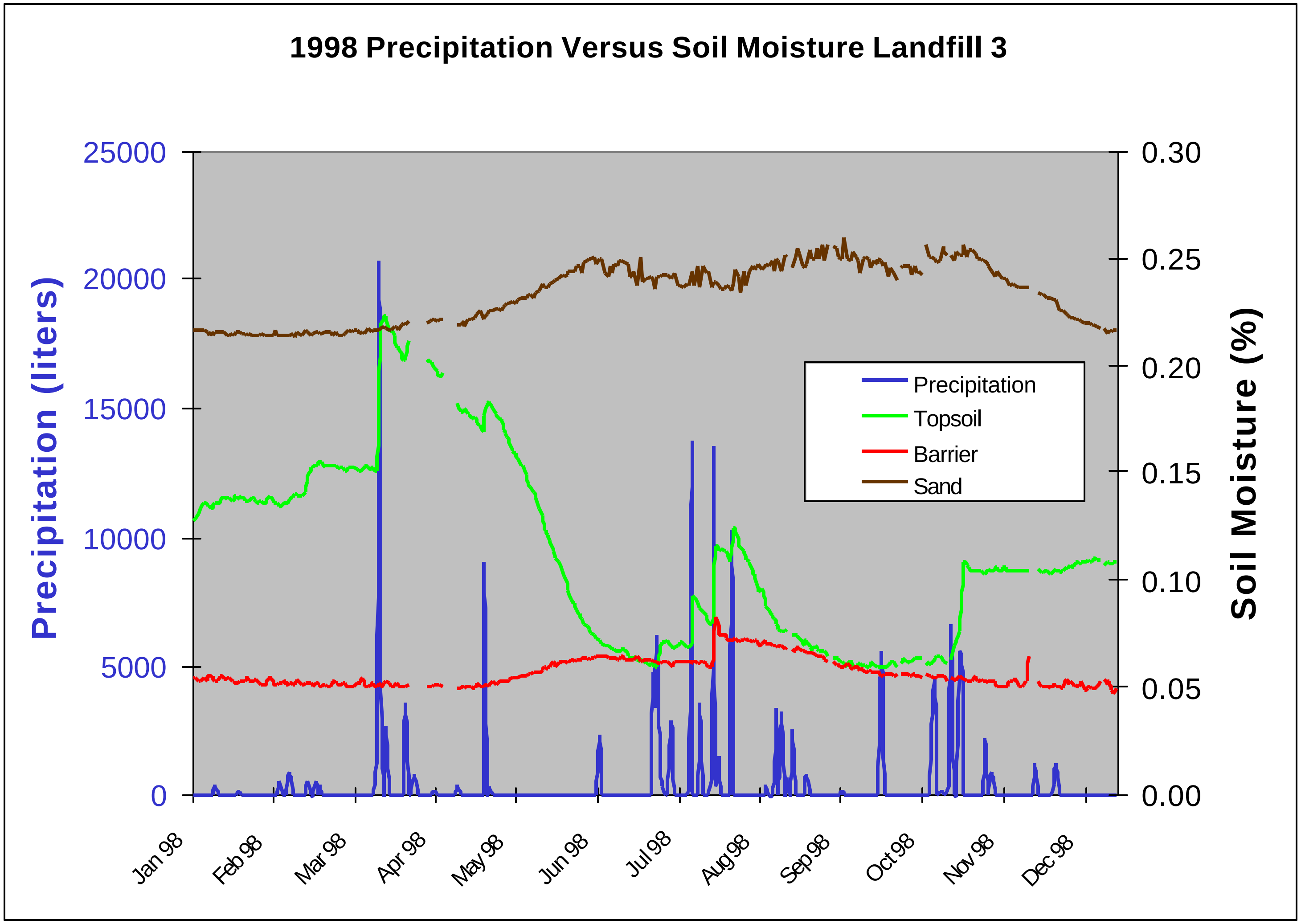


Figure D-9. 1998 Precipitation Versus Soil Moisture Landfill 3

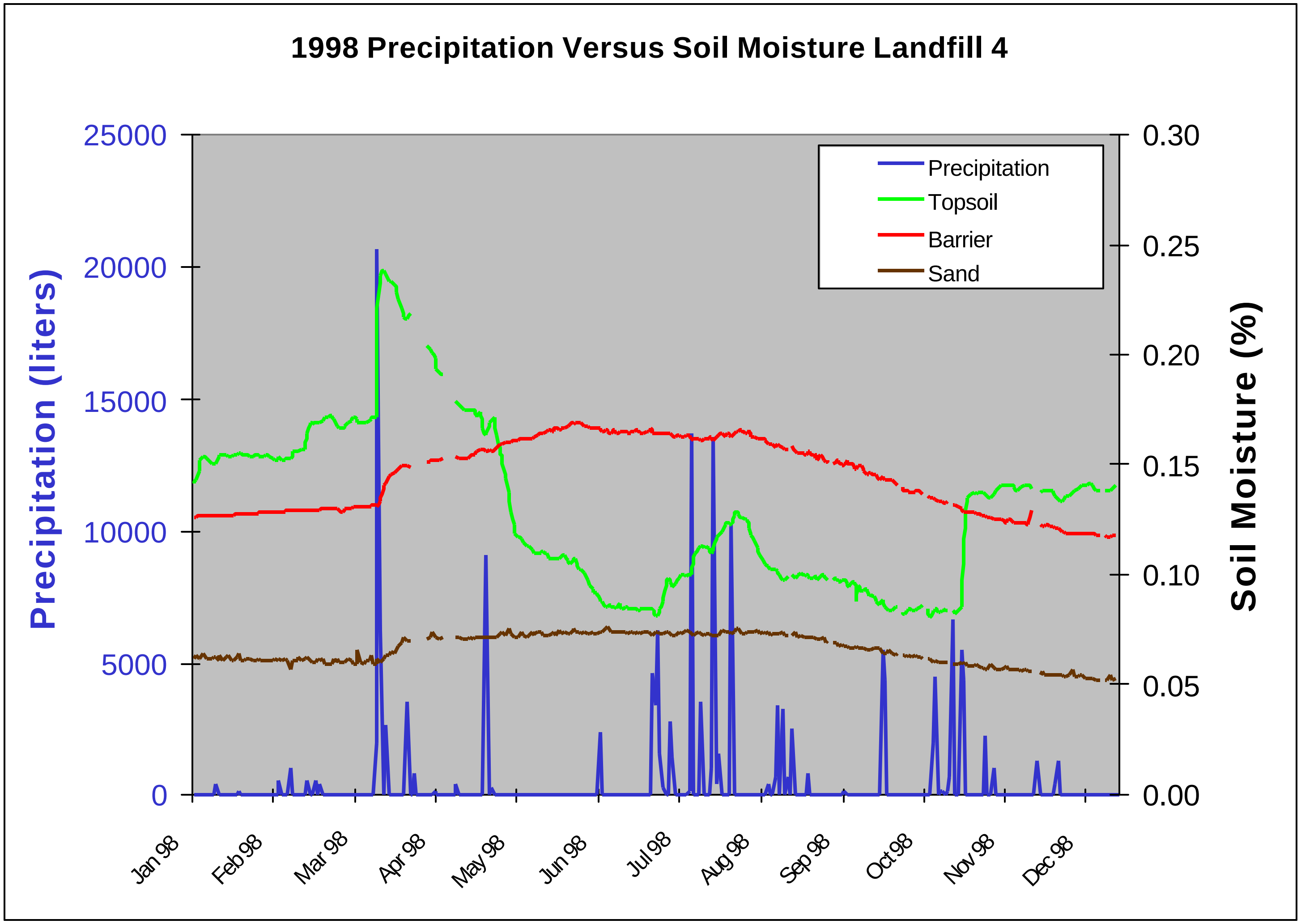


Figure D-10. 1998 Precipitation Versus Soil Moisture Landfill 4

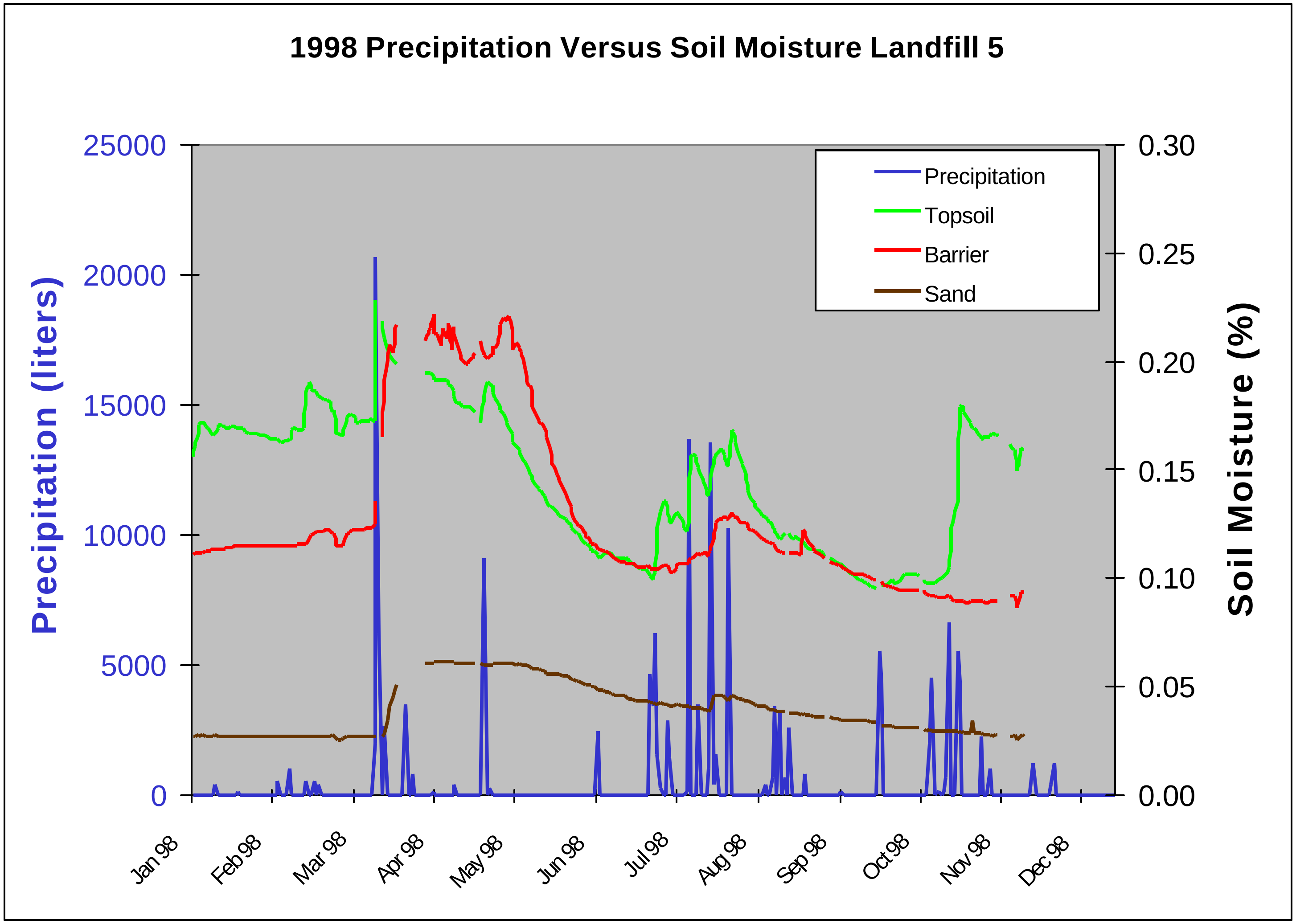


Figure D-11. 1998 Precipitation Versus Soil Moisture Landfill 5

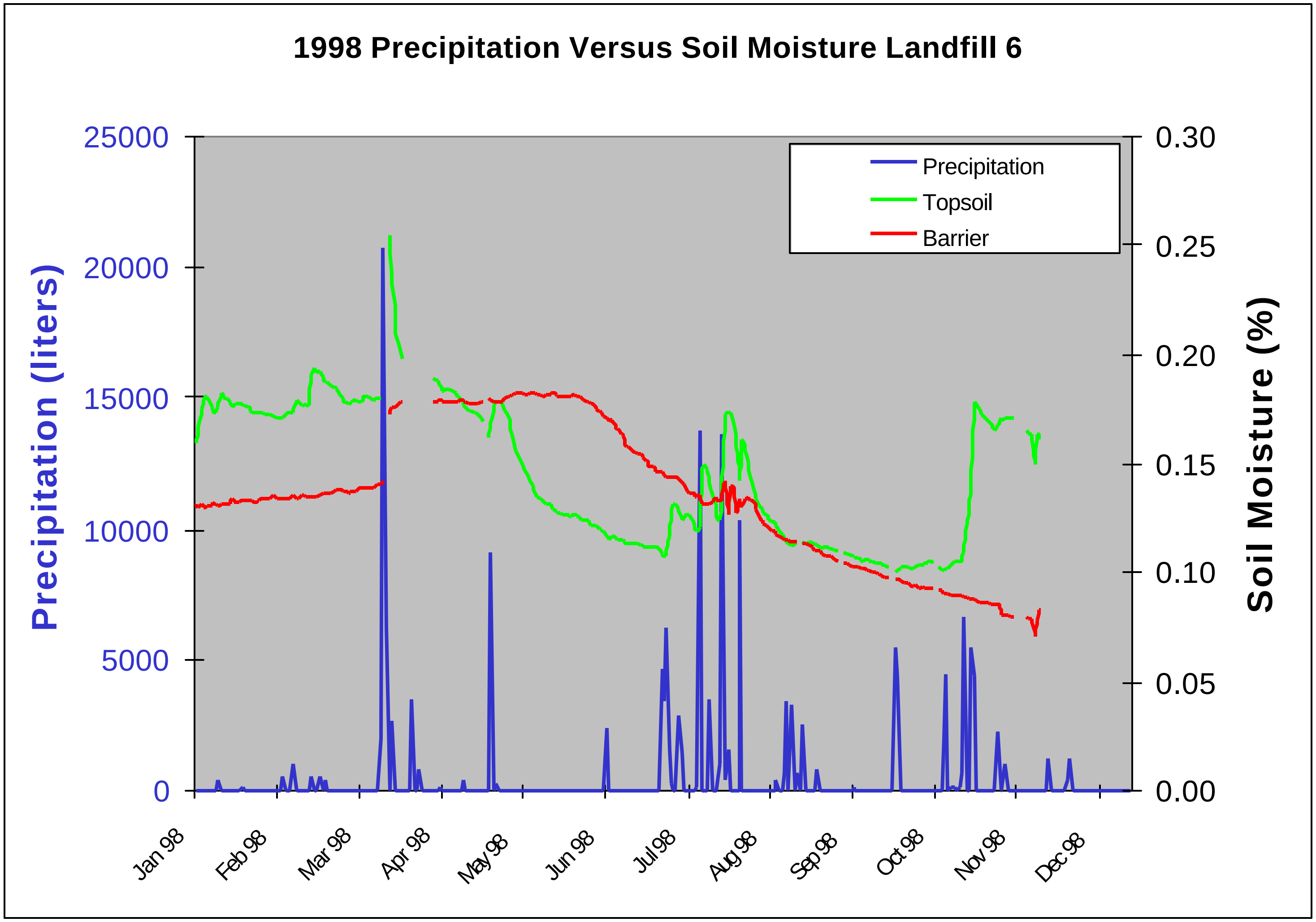


Figure D-12. 1998 Precipitation Versus Soil Moisture Landfill 6

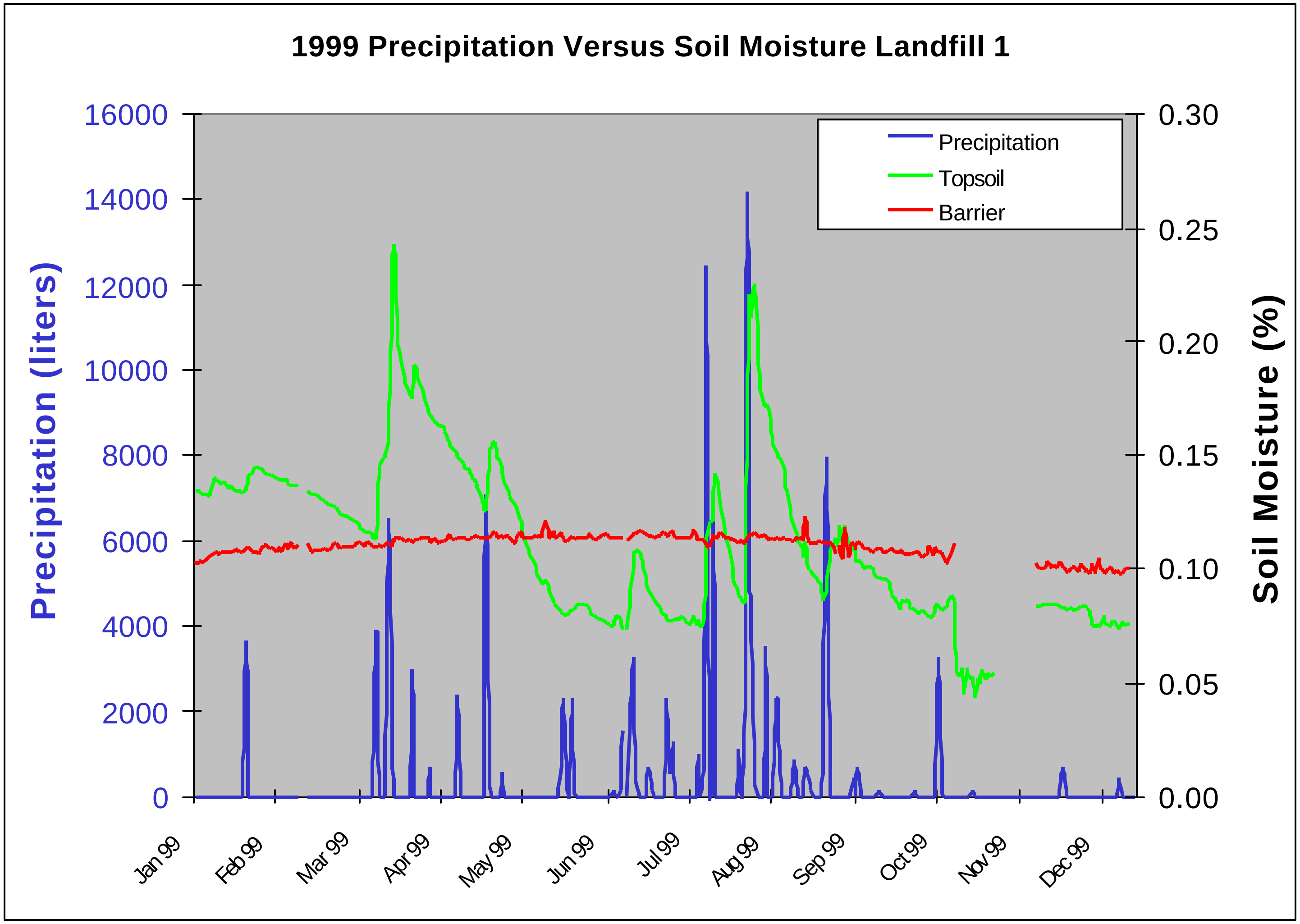


Figure D-13. 1999 Precipitation Versus Soil Moisture Landfill 1

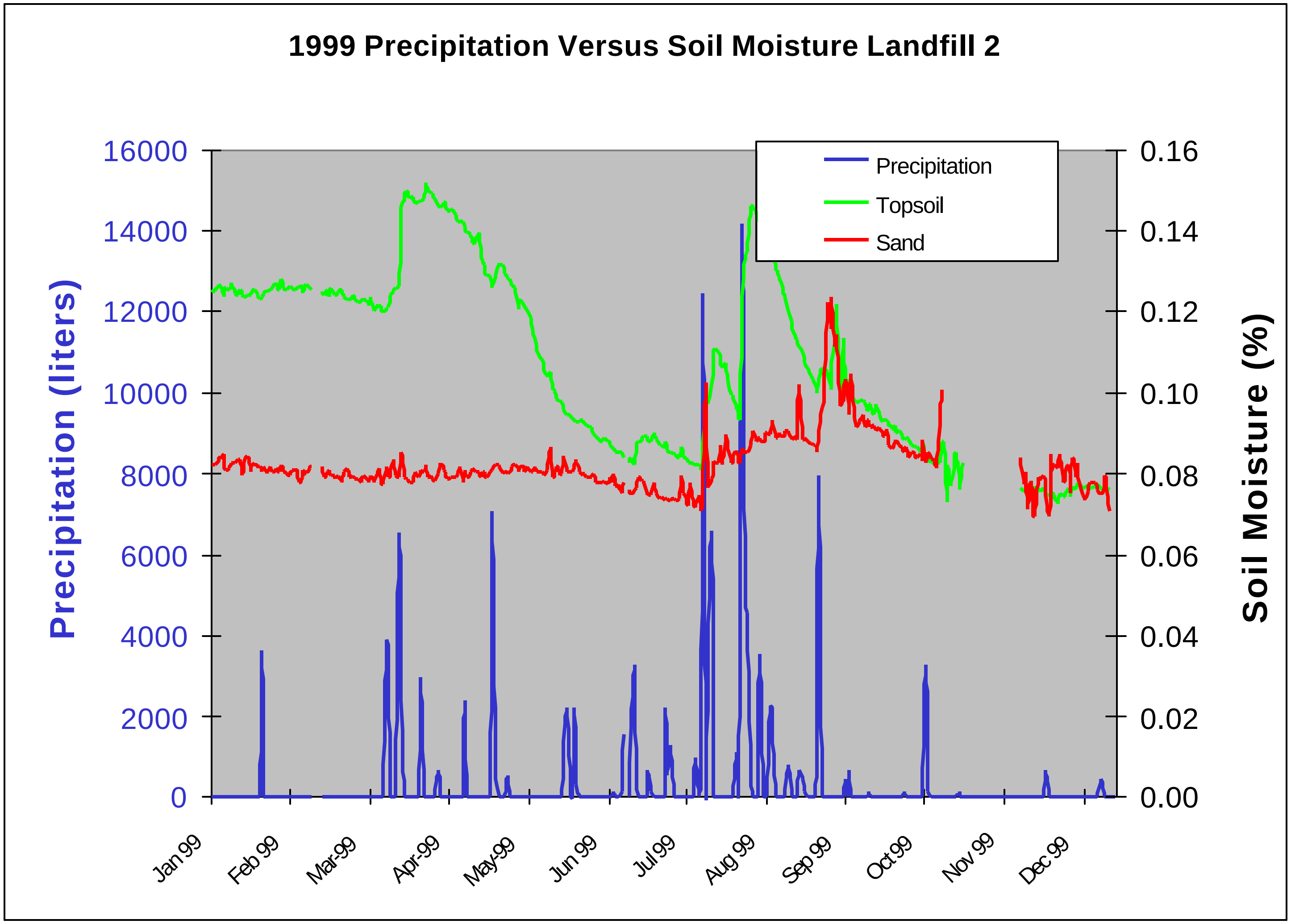


Figure D-14. 1999 Precipitation Versus Soil Moisture Landfill 2

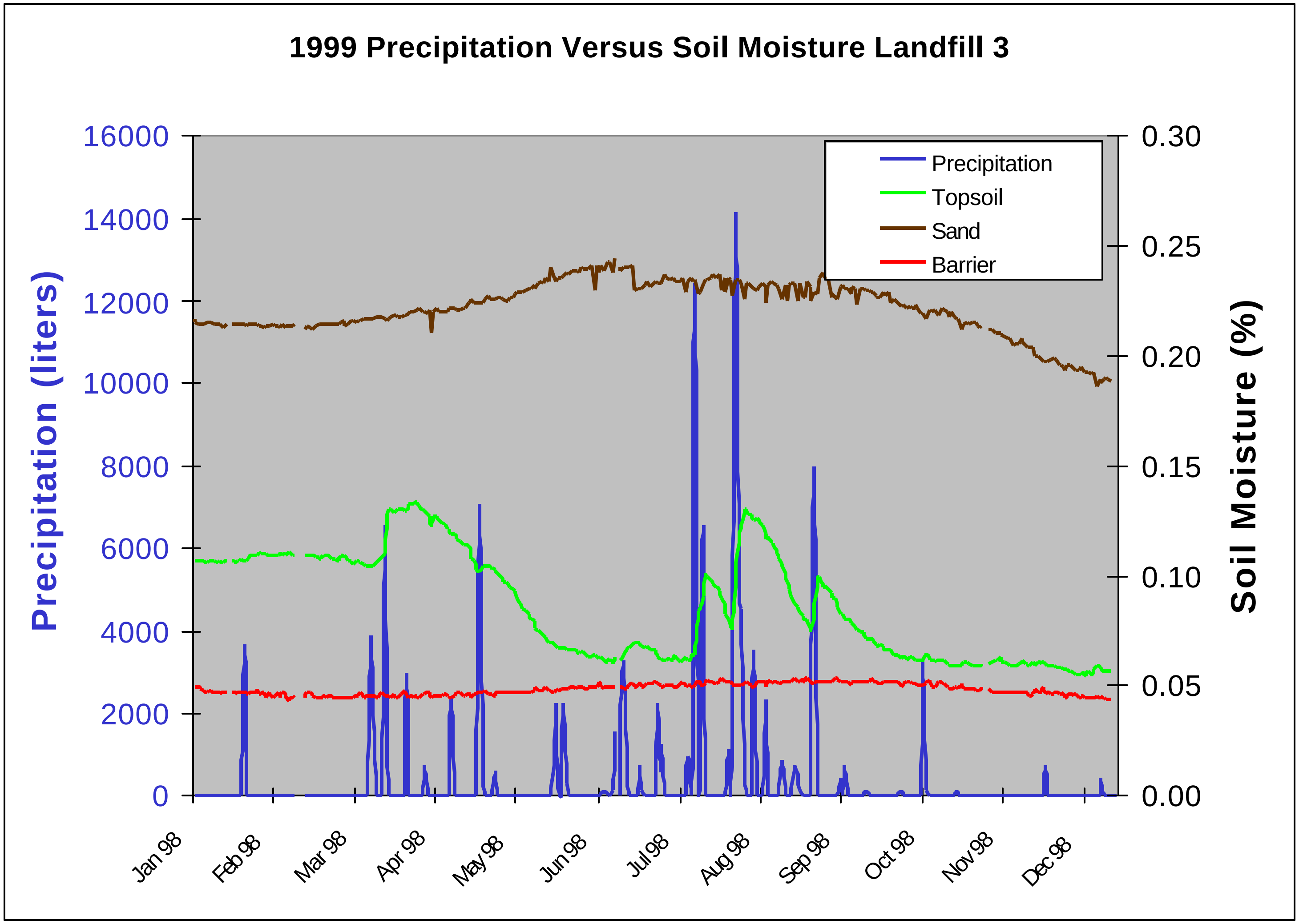


Figure D-15. 1999 Precipitation Versus Soil Moisture Landfill 3

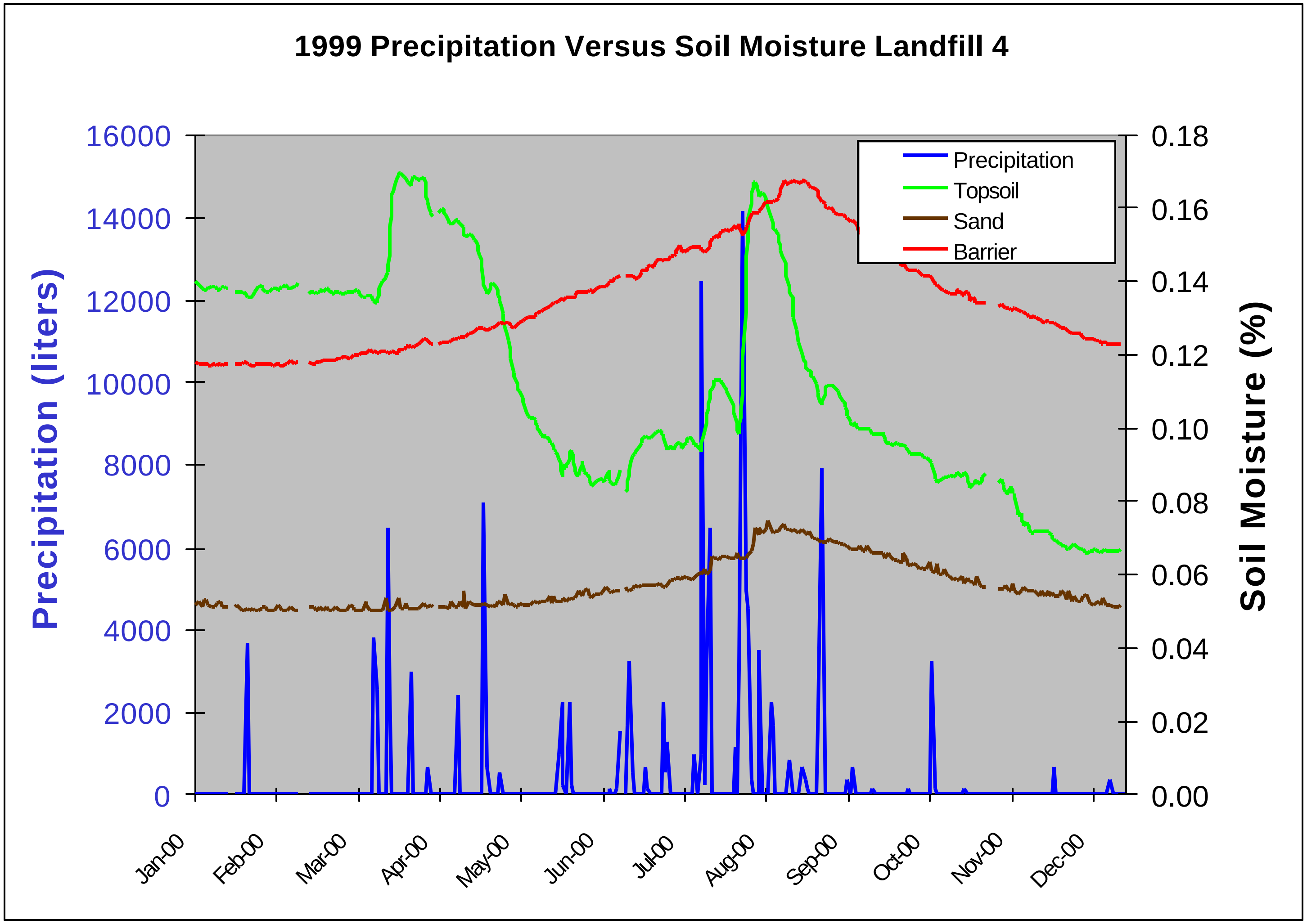


Figure D-16. 1999 Precipitation Versus Soil Moisture Landfill 4

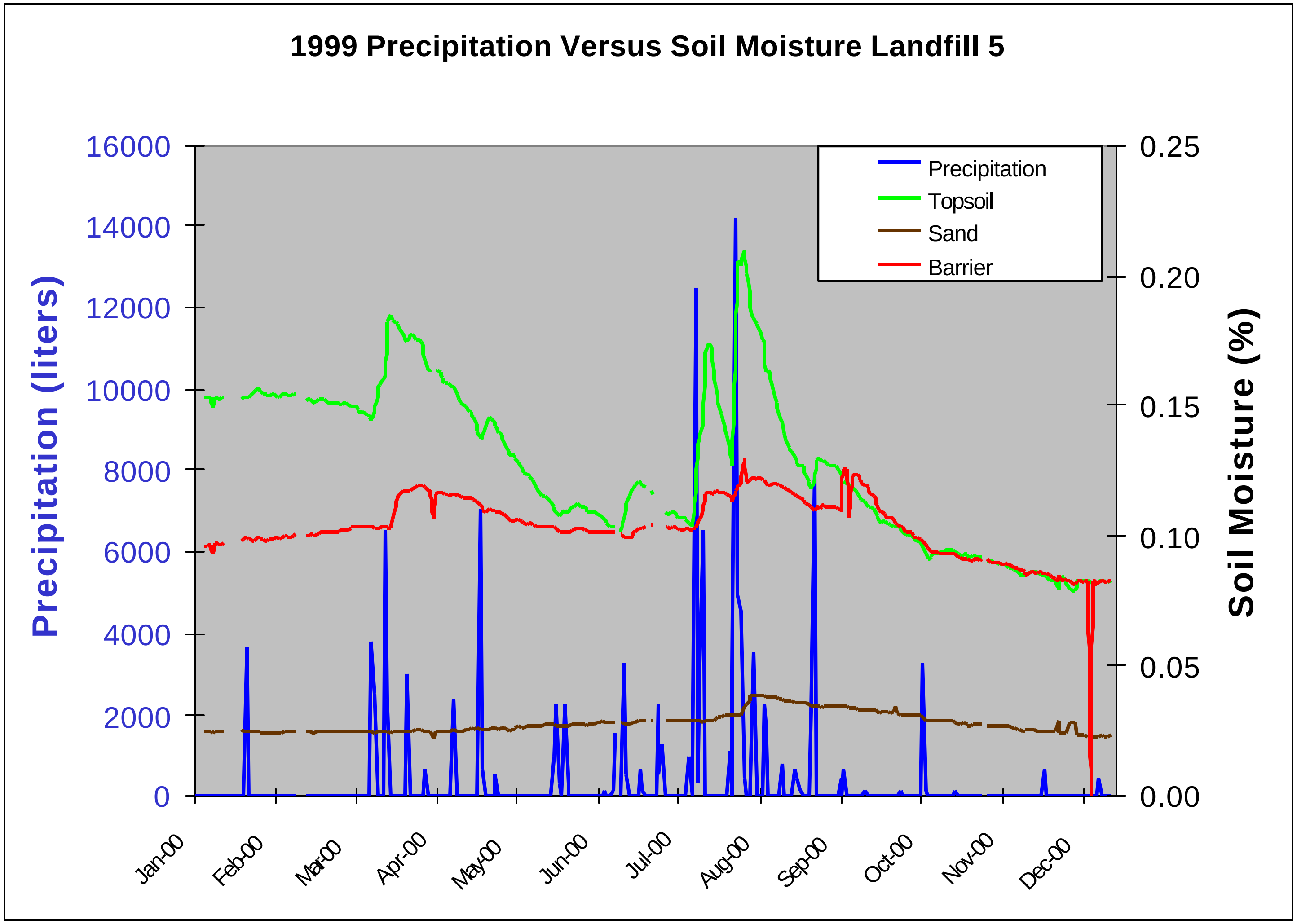


Figure D-17. 1999 Precipitation Versus Soil Moisture Landfill 5

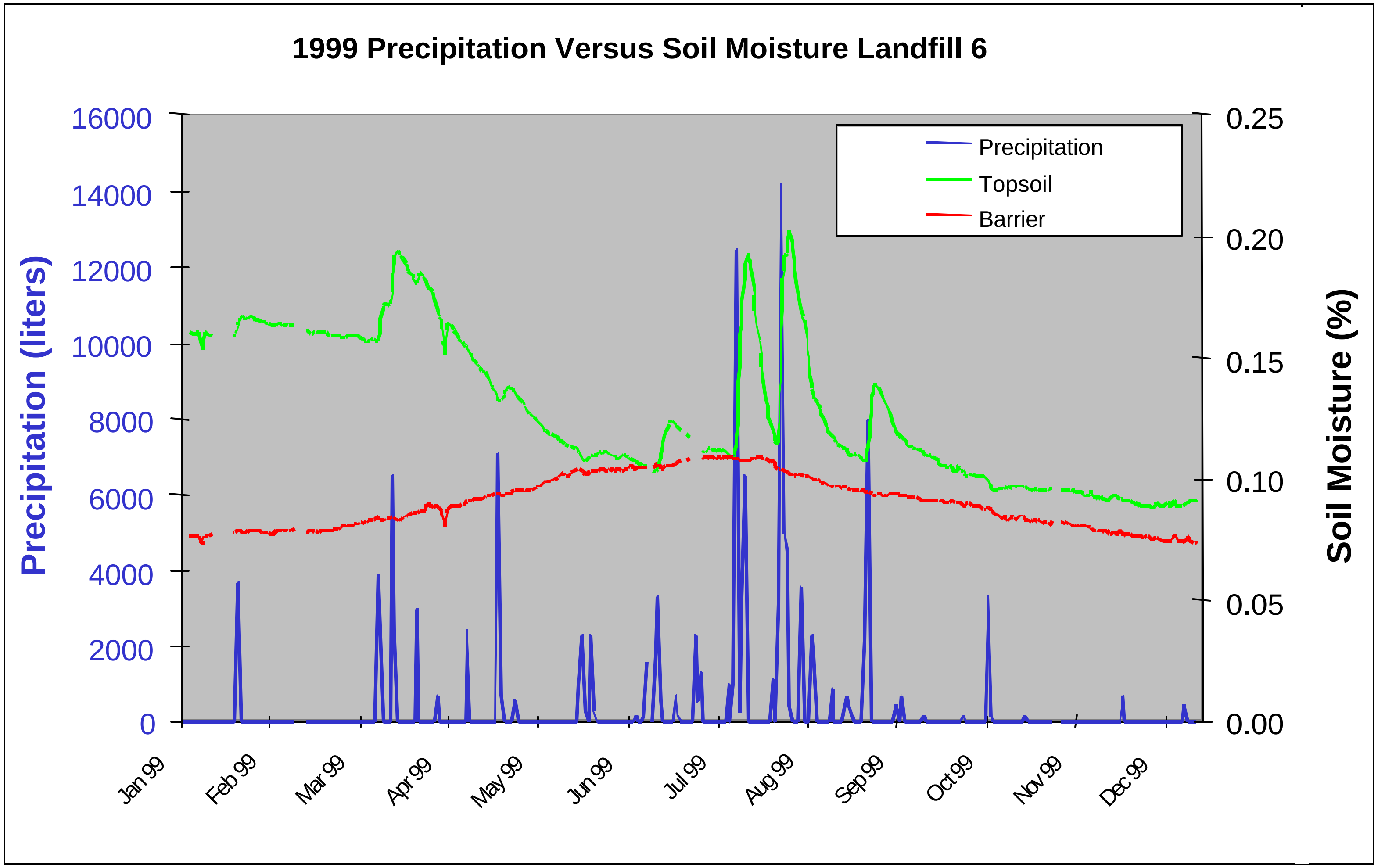


Figure D-18. 1999 Precipitation Versus Soil Moisture Landfill 6

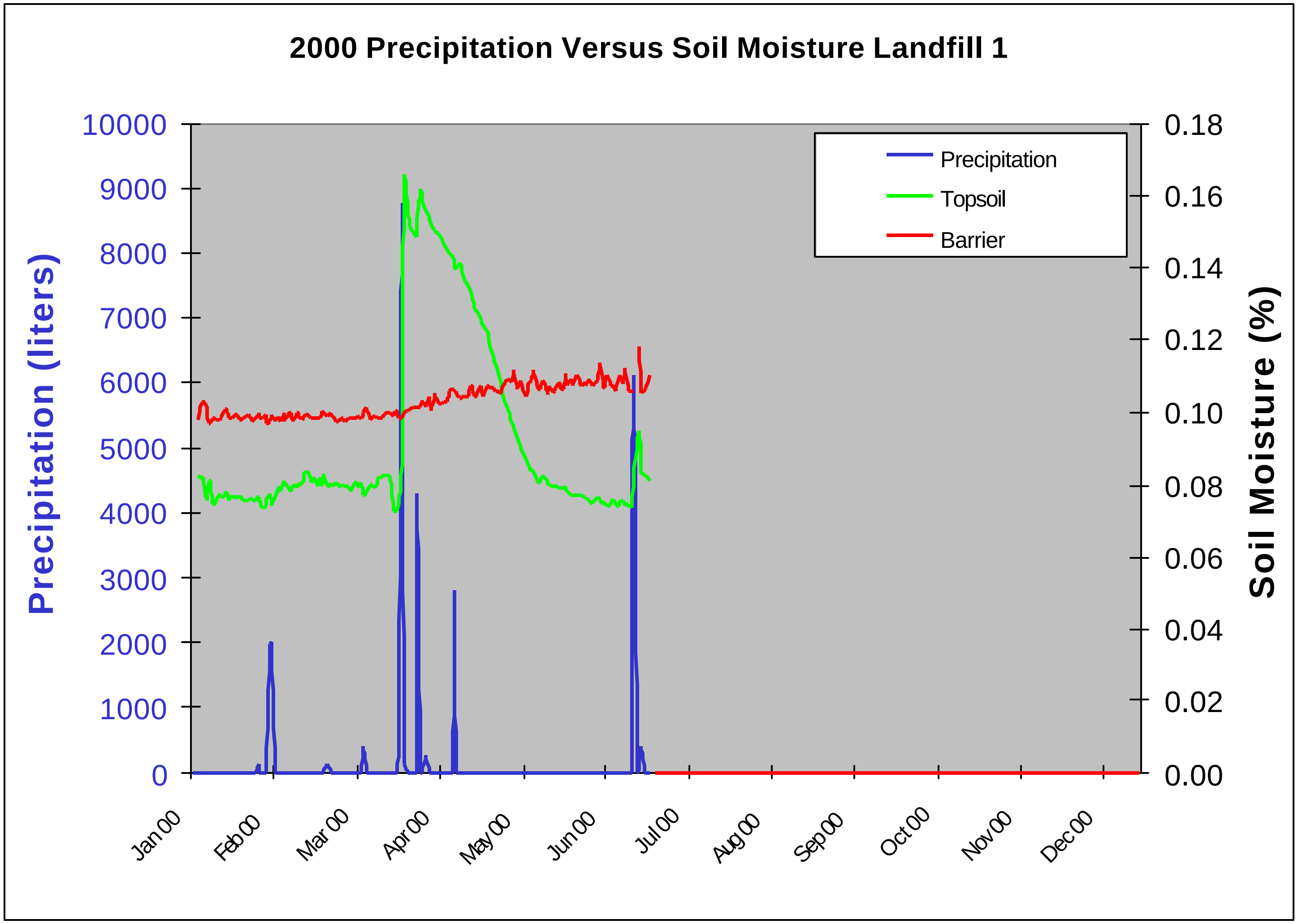


Figure D-19. 2000 Precipitation Versus Soil Moisture Landfill 1

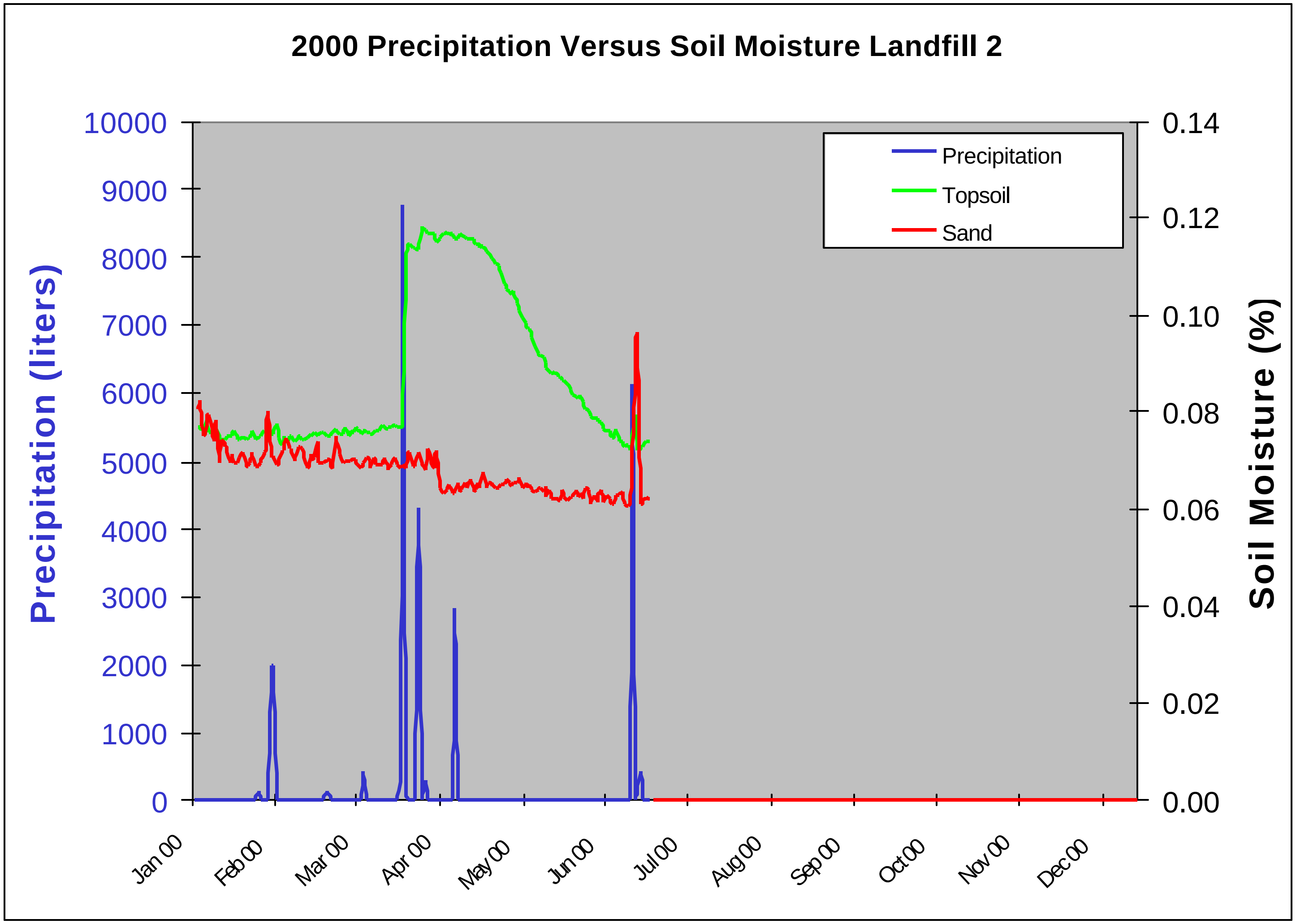


Figure D-20. 2000 Precipitation Versus Soil Moisture Landfill 2

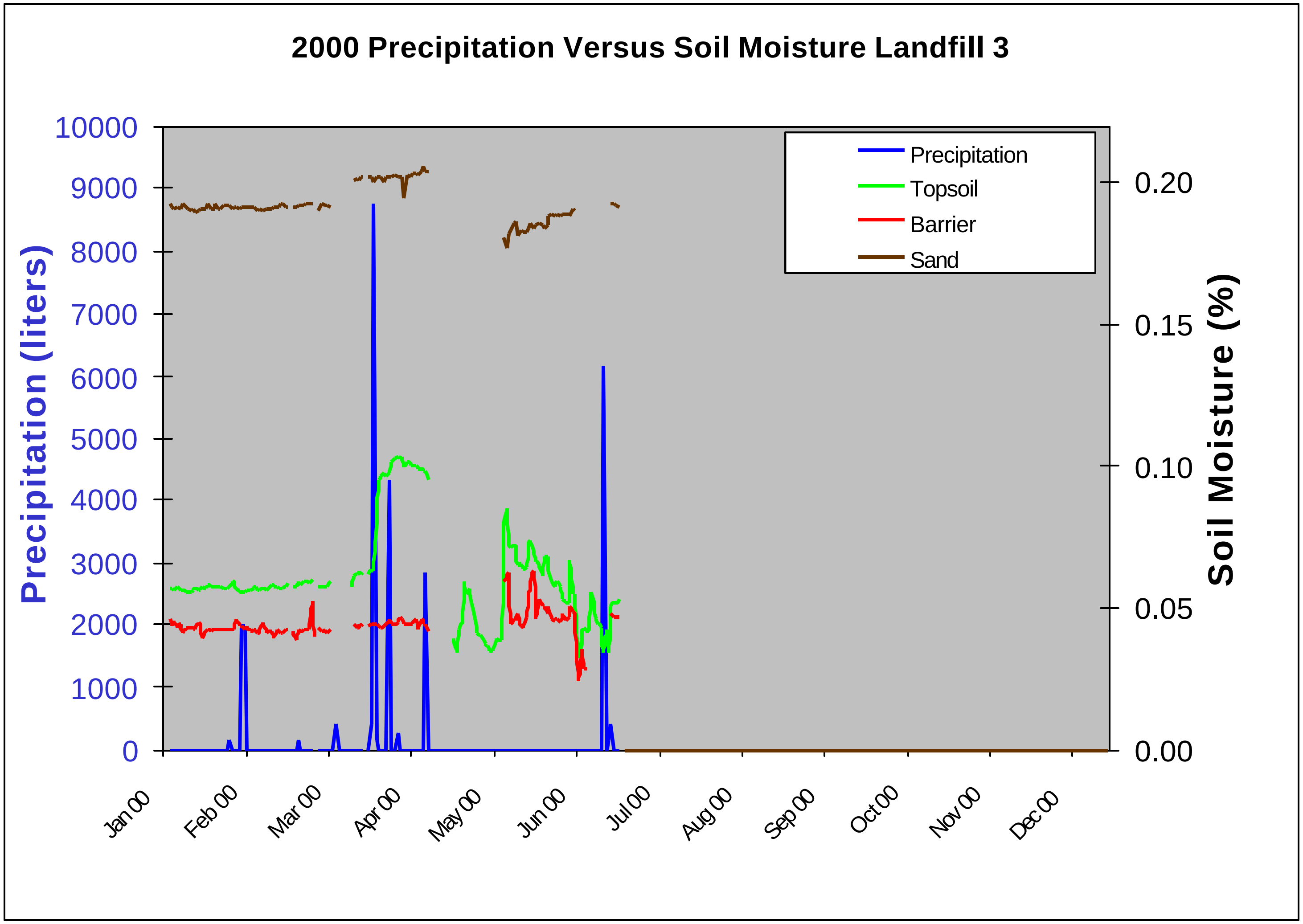


Figure D-21. 2000 Precipitation Versus Soil Moisture Landfill 3

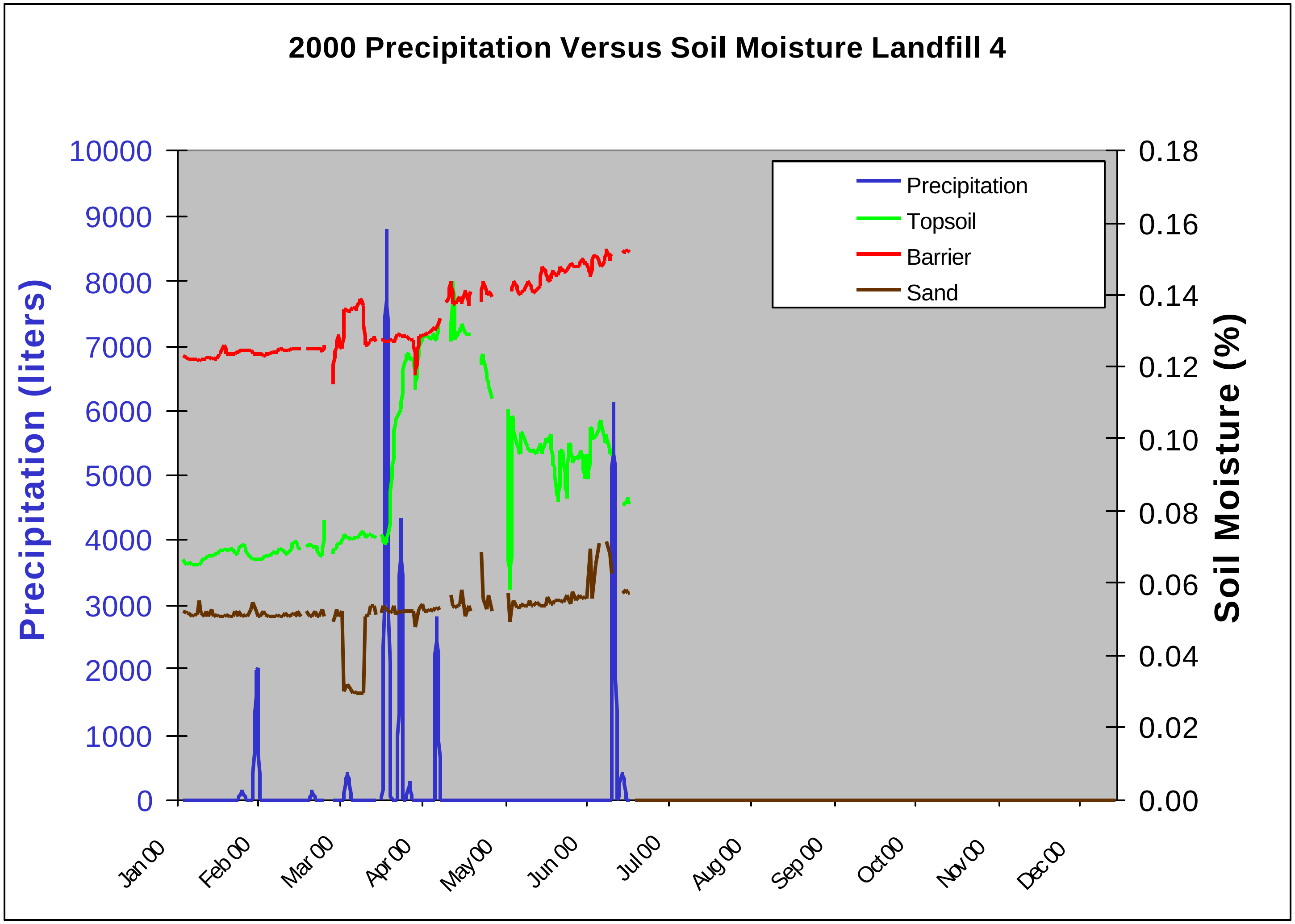


Figure D-22. 2000 Precipitation Versus Soil Moisture Landfill 4

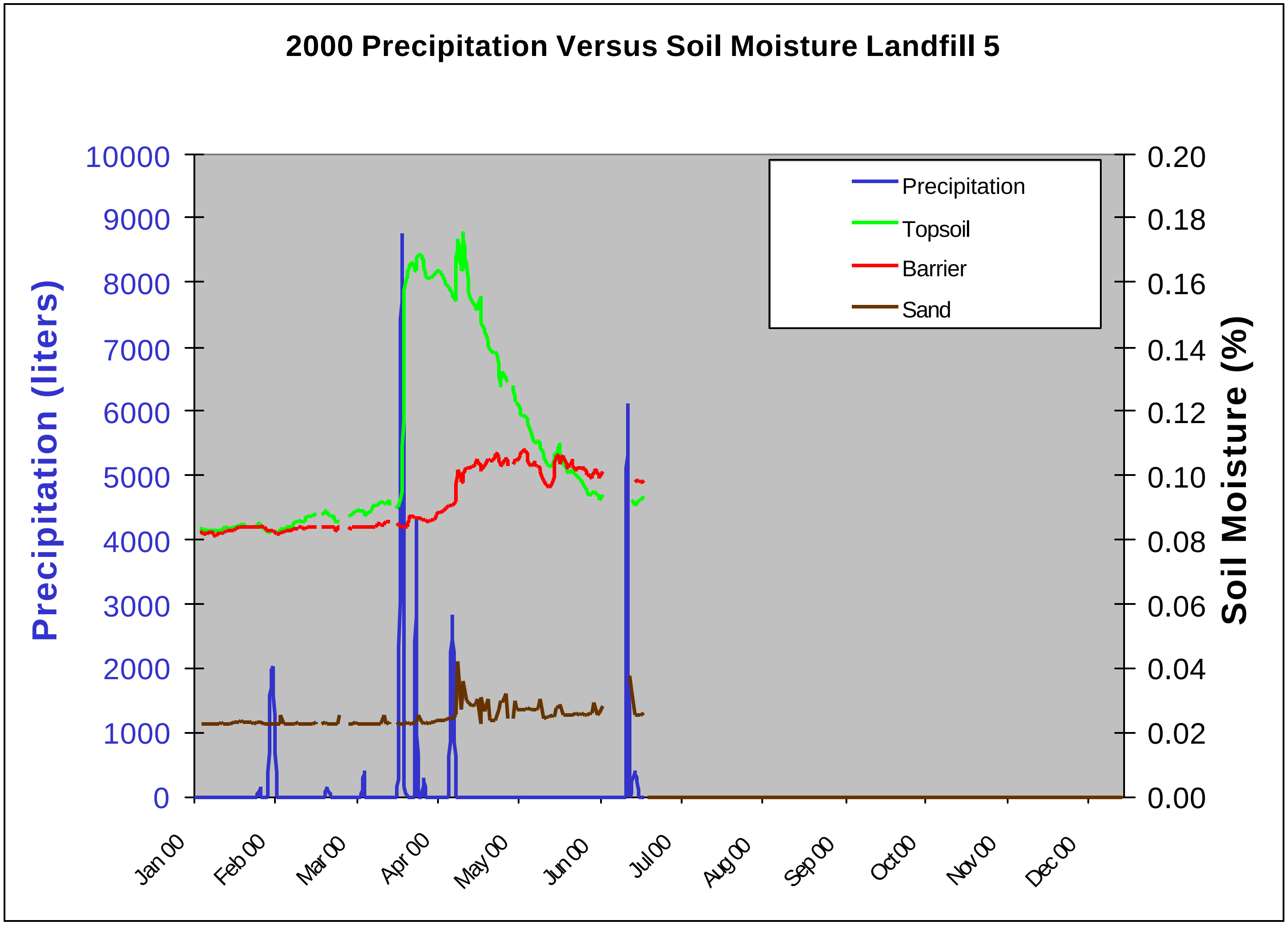


Figure D-23. 2000 Precipitation Versus Soil Moisture Landfill 5

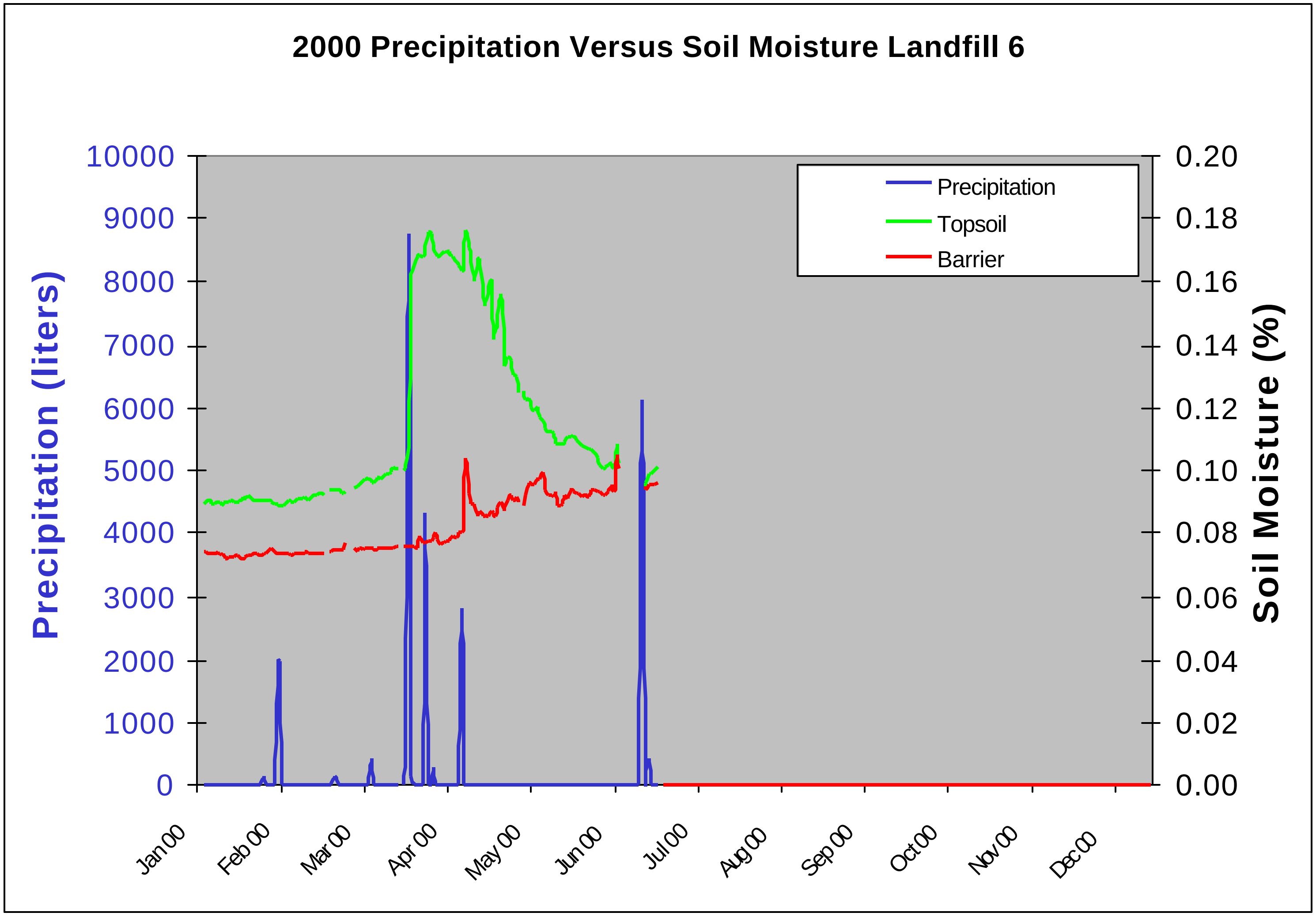
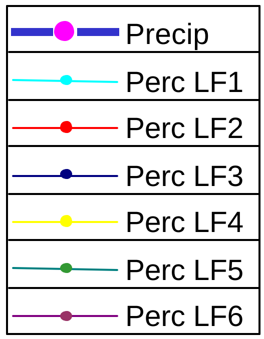


Figure D-24. 2000 Precipitation Versus Soil Moisture Landfill 6

Appendix E

Precipitation Versus Evapotranspiration



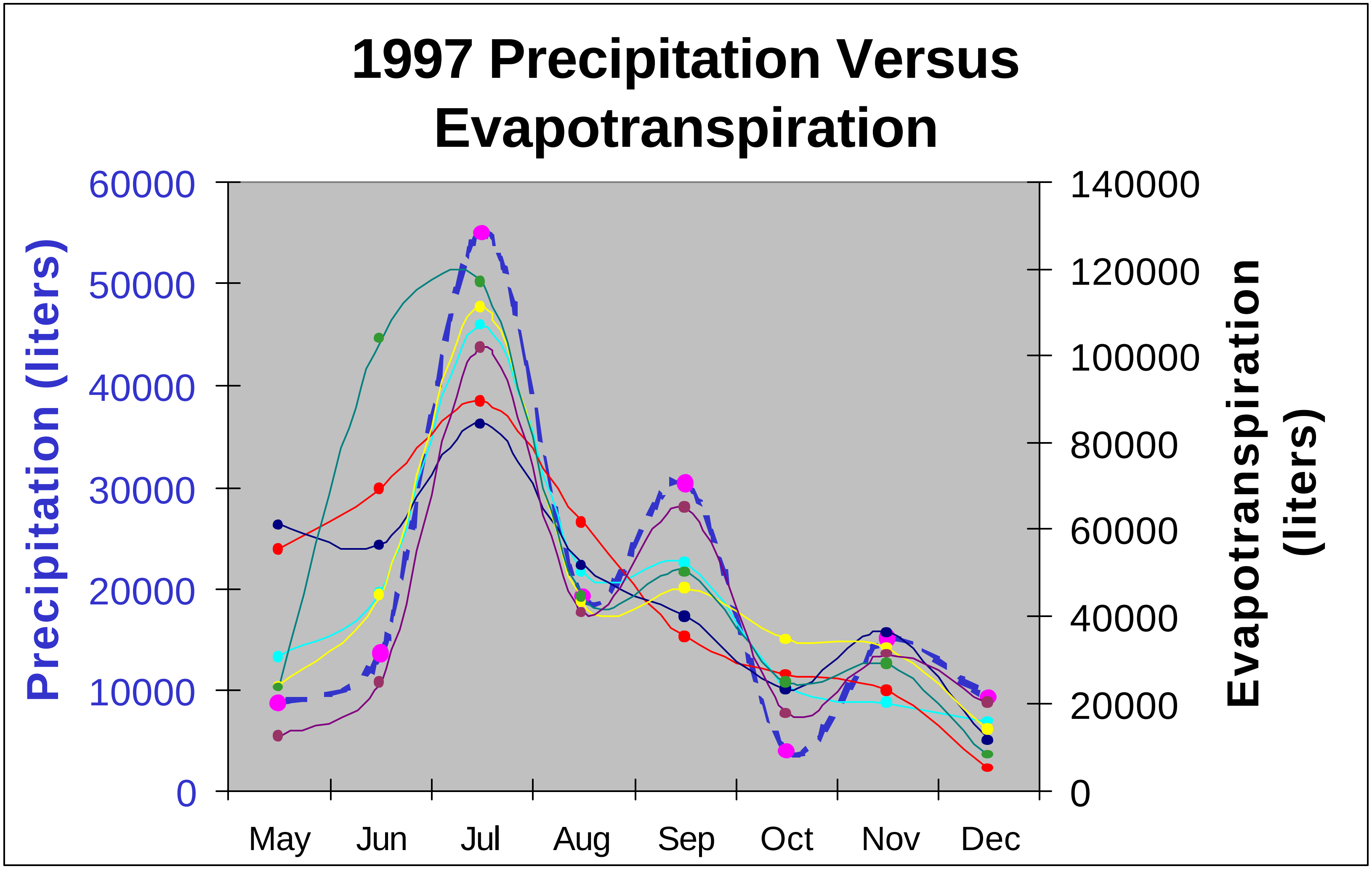


Figure E-1. 1997 Precipitation Versus Evapotranspiration

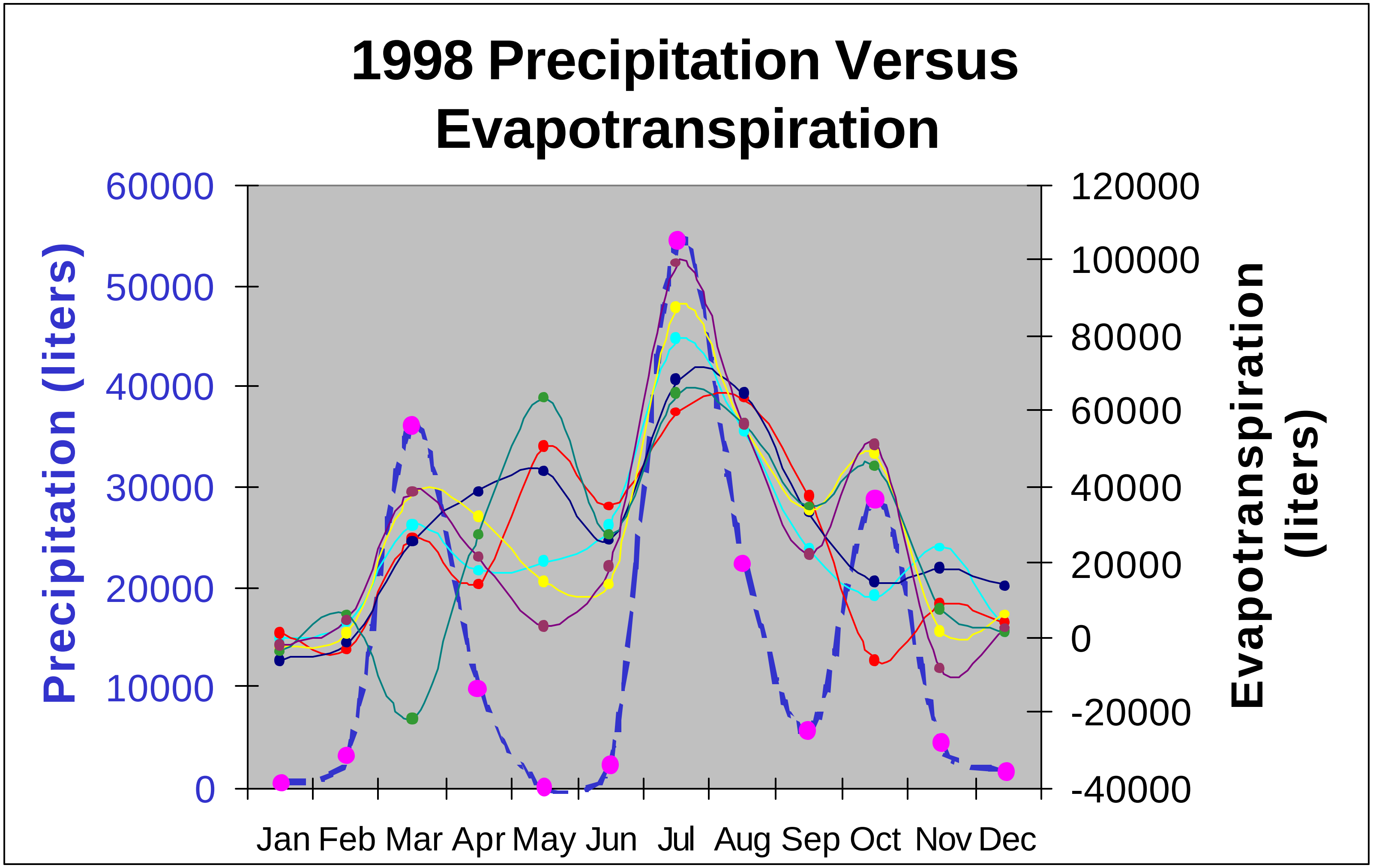


Figure E-2. 1998 Precipitation Versus Evapotranspiration

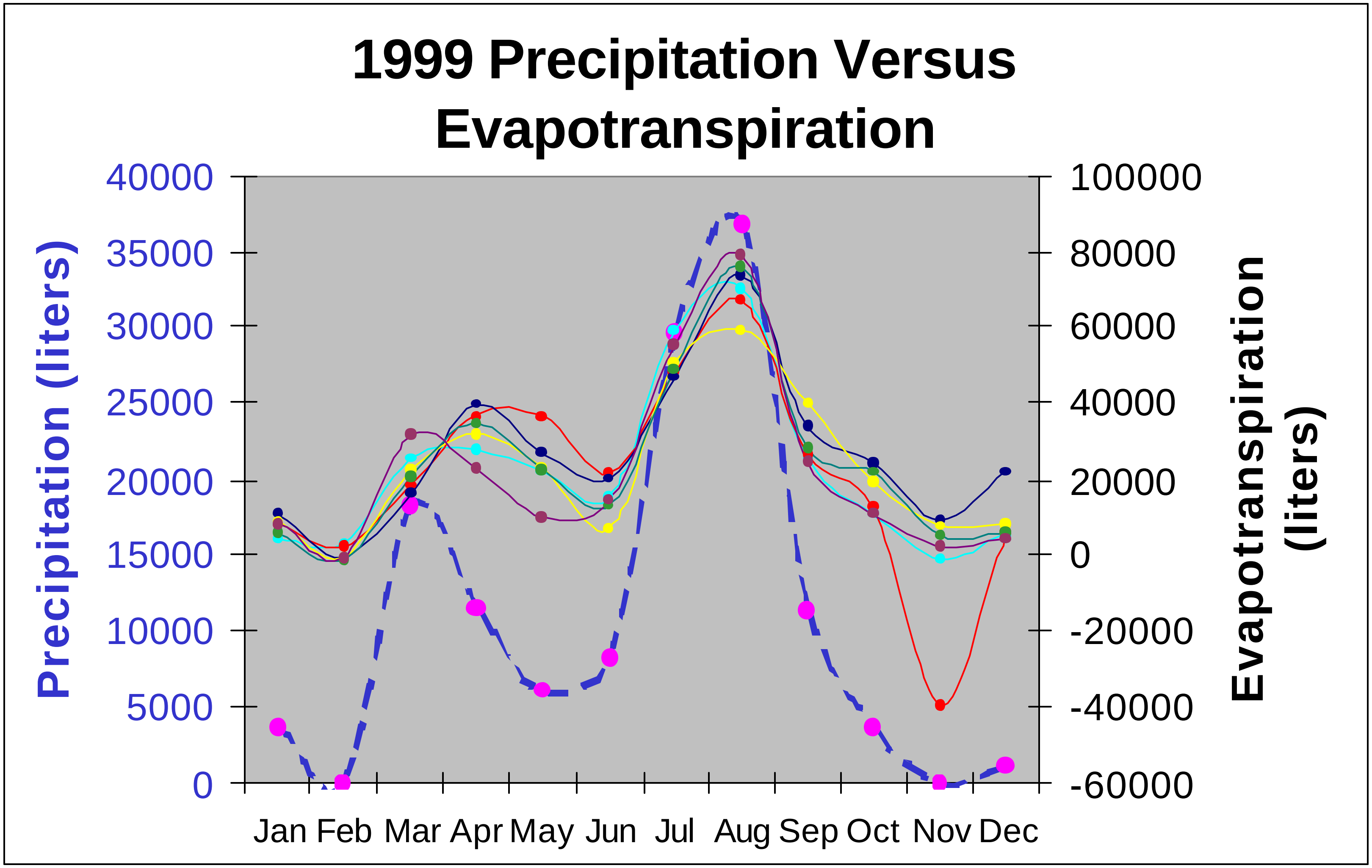
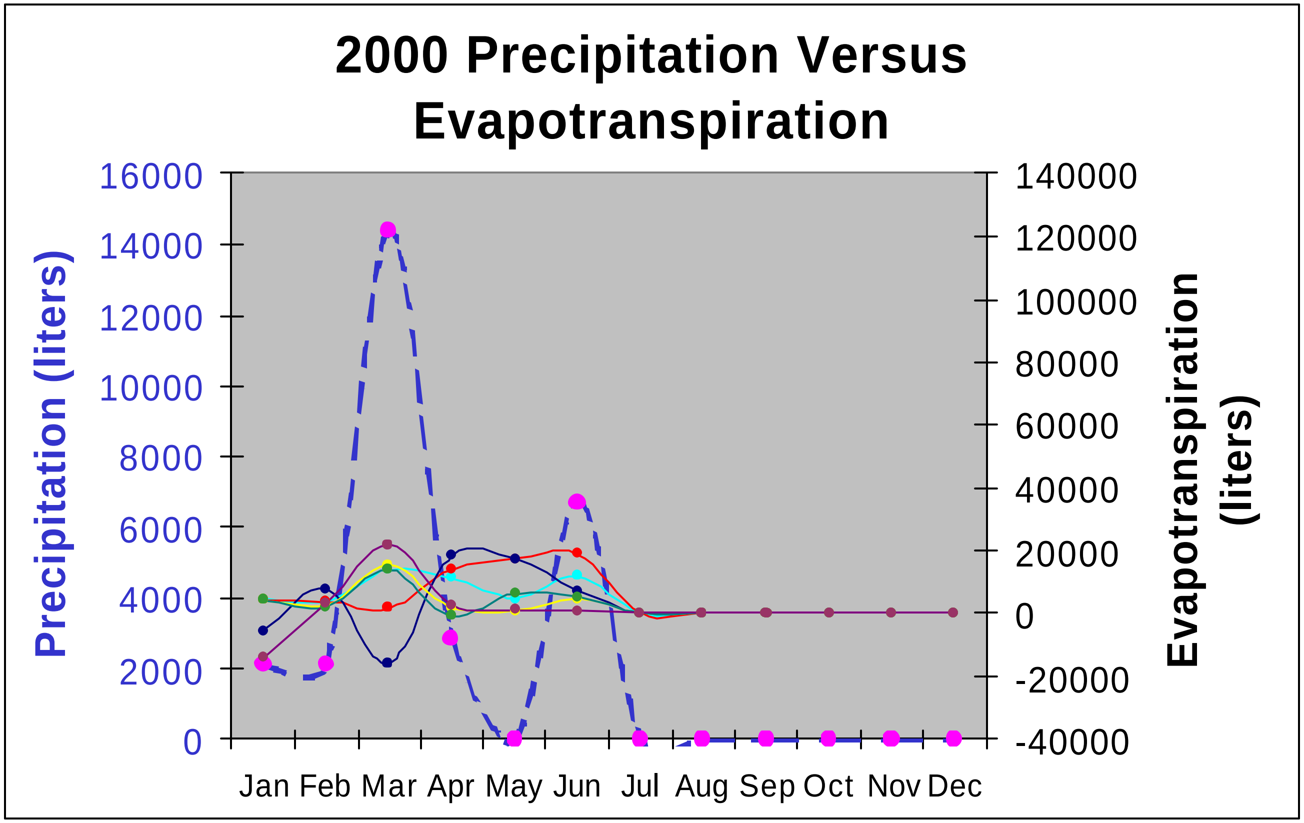


Figure E-3. 1999 Precipitation Versus Evapotranspiration



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